Master’s Programme in Mechanical Engineering

Prototype validation of device for bending and cutting coaxial cables for cryostat in quantum computing

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Abstract

This research's main focus is to help advance the manufacturing of quantum computers as a benefit to humanity. The road is long and complex but small steps throughout different people, universities and research centers is what this technology needs to achieve its full potential. Quantum computing is on the way to becoming one of the most influential technologies in human history. The ability to be able to simulate complex quantum systems will permit the acceleration in development of highly needed technologies in a wide variety of areas. Medicine, genetics, climate sciences, engineering, material sciences, etc. will see a great boost in discoveries and technological advances. For all of this to happen, research into the problems or limitations blocking further development need to be funded and pushed forward. The bottleneck in this advance will jump areas of science fairly quickly and constantly. The main areas required can be roughly divided in computer science, material sciences, manufacturing and R&D. This research focused on the manufacturing part, specifically in the superconductive cables used to communicate with the quantum chip. The automation of the manufacturing of these cables has been lagging behind since the required amounts have not yet been enough to justify the development of a machine to do it, until now.

This research was done to validate and calibrate a prototype to measure, bend and cut the coaxial cables with high accuracy and repeatability. A process specific failure mode and effects analysis (PFMEA) was followed to identify the main failure areas which were tackled one by one. After this the validated prototype was used in pair with Go-NoGo gauges to validate the quality of the manufactured cable.

The prototype has the required reliability and robustness to enter the production plant and start manufacturing the superconductive coaxial cables, which is an important demonstration of a well executed PFMEA.

Keywords Quantum Computing, Superconductors, SCuNi, Coaxial, Thin cable bender, bending machine, cryostat

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Preface

This research idea started from my curiosity to improve processes and my desire to better utilize human resources by automating repetitive and simple tasks, allowing technicians to excel in difficult and precise tasks that machines have a harder time doing.

I first want to thank Bluefors for the assistance and openness to help in the process of creating this machine. Big thanks to Antti Lumo for believing in me and allowing me to develop and create outside of my actual tasks at work. Thanks to Mikko Peurala, Ville Nuutinen, Toni Berg, Neil Owens, Mika Ollila and the rest for always being open to listening to me.

Thanks to my supervisor Petri Kuosmanen and my advisor Niko Tapanainen for their ideas, advice, support and constant push which allowed me to finish this research in time, you will always have a special spot in my mind.

Gigantic thanks to my wife Vivika Viikari for her constant support and infinite love towards me and my crazy ideas, thank you for being there whenever I need it, even when it's hard. Life would be way harder without you by my side.

Thanks to my family for their support, even being so far I can always feel them so close. Big thanks to my parents for their constant sacrifice to give me a better life, also to my brothers and sisters for always being there for me when I have something to say. Together we are stronger. Thanks to the Viikari family for taking me in as one of yours and constantly helping me so selflessly.

Thanks to my friends for being such an essential part of my life. Erick, Edu, Roy, Andres, Pablo, Jorge, Poncho, Gustavo, Paavo, Veer, Rami, Alice, and so many more, I feel your encouragement every time I talk to you, I will forever be thankful for your help.

Thank you Fernando Gomez Urquiza for teaching me so much and helping me become my better self. You will always be a role model of mine.

Dearly,

Fernando Marquina Magaña
14/05/2021 in Vantaa

1 Introduction

1.1 Background

Quantum technology has proven and will continue to prove an essential tool for humanities development going into the future, the ability to simulate complex and quantum experiments will prove priceless to a species trying to develop further than ever before. Medicine and genetics will be pushed through new boundaries beyond the wildest dreams (Solenov, 2018). While global warming and complex ecological, soon to be, disasters will be dealt with knowledge and power by precisely being able to calculate the outcome (Frolov, 2017). All of this will be fuelled by the tools provided by quantum computing and AI. With almost unlimited computing power compared to classical supercomputers, continuous growth and life improvement for humanity is almost certain (Schradle, 2020). There will be lots of challenges in the way, but the great collective mind of humanity will surely push through.

In its most basic, quantum particles are particles which follow quantum mechanics laws instead of classical mechanics. This allows for complex behaviours like “superposition”, “entanglement” and “interference”, which allow exponential amounts of information to be stored in what is known as Qubits. Classical computers work with bits which can be in one of two states, either a one or a zero. This means that adding one more bit, increases the number of possibilities by one, meanwhile Qubits exist in a superposition of two states, known as the cloud state, in which they can represent all the possibilities between a zero and a one at the same time, their true state is only revealed when the qubits are “observed”. Which means being measured or interacted with or it can mean any form of energy interacting with them, which is a plus and a minus at the same time. The possibility of one or the other being observed is known and this helps run the calculations or operations computers need to work (Dahl, 2015).

For all of this to work the quantum chip needs to be kept as cool and with as little interactions to the “outside” media as possible. This is achieved in a dilution refrigerator known as a cryostat which keeps the quantum chip as cold as possible, close to 0.015 Kelvin and in as close to absolute vacuum as possible. The cooling process is achieved by two in line refrigeration cycles, and a final dilution refrigerator cycle, which uses the basic property of entropy to extract heat from its surroundings by mixing two different isotopes of helium (Mandelis, 2020).

Superconductive coaxial lines are utilized to communicate with the quantum chip taking advantage of their superconductive abilities at extremely low temperatures; microwaves and radio frequencies are sent and received through these cables, allowing scientists to utilize the computing power. These cables are utilized because of their fast data transfer abilities and their extremely low thermal conductivity (Mandelis, 2020).

With Quantum supremacy achieved and large qubit chips under development the race to 100-qubit is close to finding a winner. 100-qubit chip would mean classical supercomputers to the power of thousands. The importance and focus of 100 qubits appeals to the significance of rounded base 10 numbers and also it is an important exponential number with which a new metric can be built upon. This kind of computing power opens great opportunities to, science, engineering, technology, social sciences, genetics, medicine, etc. Allowing research to accelerate at an exponential pace (Krinner, 2019).

Figure 1. Open Bluefors XLD dilution cryostat (Bluefors, 2021)

1.2 Research problem

This study dealt with the upcoming problems encountered by the fast evolution of quantum computers and the race to make better and bigger cryostats (Krinner, 2019). Specifically, it focused on the coaxial communication cables made of superconductive material SCuNi with a thickness of 0.86 mm. It browses through the process of ideation, design, manufacturing of a prototype to measure, bend and cut the lines to size, and then it goes in depth on the testing process required to manufacture the final coaxial cables. Previously this was a process mostly done by hand by highly qualified technicians, which is unable to keep up with the demand in the upcoming years. The commercial options available for this were analysed and discussed but it is important to already mention that these machines do not possess the required precision, quality or cable management systems required by the delicate coaxial cable used in production.

Figure 2. Assembled superconductive coaxial cables with a loop (Bluefors, 2021)

An automated wire bending machine is used to create accurate and complex bends in a variety of materials, cross-sectional shapes, and sizes. Automated wire bending machines may be operated, for example, through computer numerical control (CNC). CNC wire bending machines allow a user to design a shape using a computer or other processing device, and have the machine create the shape consistently according to a part program. By automating the wire-forming process, complicated parts can be made beyond the capabilities of ordinarily skilled human craftsmen. Further, CNC wire bending machines may be used to create precise parts repeatedly, reducing the need to inspect or rework individual parts.

With the previous geometry, the cables were manufactured with a loop in the middle part of their length as shown in figure 3, this allows for thermal expansion and compression, which occurs in the heating and cooling cycles of the cryostat. The main issue encountered with this method of strain relief is that this loop creates a point where the cable passes next to itself and allows contact, this contact and the vibration of the whole system creates friction, which in turn creates heat, affecting the cooling down time of the system. To counteract this, a cotton thread is tied in a knot in the point where the cable contacts itself as seen in figure 4, this solves the friction/heating problem, but it also creates a manufacturing nightmare where a technician needs to tie all these knots by hand. The solution and experiments are discussed more in chapter 3.3.

Figure 3. Coaxial cable with previous geometry, loop

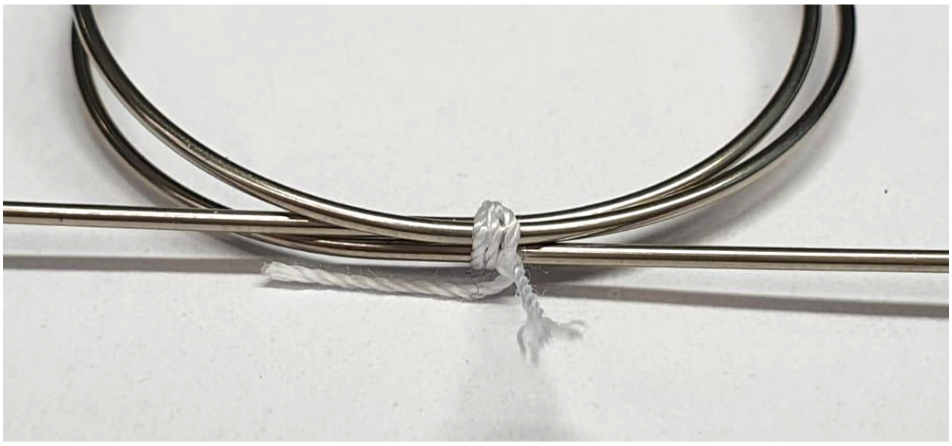


Figure 4. Coaxial cable with cotton knot to eliminate friction and heat induction

The main research question is: What is the production capacity, quality, accuracy and repeatability of the bending prototype?

This means the research goes through the different methodologies there are, to validate prototypes, with quality control as the main focus, the most fitting was chosen for this prototype. Then, said methodology was implemented and tested with the prototype to validate its functionality and aiming to answer the research question.

1.3 Aim of the research

This research focused mainly on the testing phase of an already built prototype and described the methods followed, to accomplish the desired functionality and for it to be integrated into the production line.

It explores in detail the different variables that needed to be tweaked to reach the goals and answer the research question. It focused on the quality of the final cable after it goes through the process of the bending machine. It used Go-NoGo gauges to visually inspect the main attributes of the cable and how changing variables in the code affect the final product.

1.4 Scope of the research

This research did not focus on the design and prototype iteration as this has already been discussed in the research paper "Device for bending and cutting coaxial wires for cryostat in quantum computing". It did not include the specifics of the PLC controller or anything related to the programming, except a brief explanation of the parameters that needed to be changed for the tuning.

1.5 Methods

The research done for the validation of the prototype focuses on researching available commercial machines with similar functionalities, and patents focused on machines that bend thin cable. The prototype was tested and validated following a combination of methods to take machines to full production, including process specific FMEA, Go-NoGo gauges, while also researching KPIs, design of experiments and the taguchi method. This is discussed more in depth in chapter 3.

2 State of the art review

The following represents the research done to understand the position of this research in respect to all previous work done in this topic. It includes a description of superconductive coaxial cables, state of the art and patent review. It also explains the methods to validate prototypes and their use scenarios.

2.1 Superconductive coaxial cables

Superconductive coaxial cables are one of the most important parts of quantum computing since they allow communication to and from the quantum chip. This has allowed the design of low loss coaxial transmission cables with improved characteristics. They are essential to be able to transmit signals without transmitting heat from the hot parts of the cryostat to the cold parts. They also need to be made specifically for cryogenic application since the differential of temperature from one end to the other is quite elevated, the most elevated being from 300 Kelvin to 50 Kelvin in 200 mm. Attenuation and bandwidth of these thin coaxial cables is now comparable to large room temperature coaxials. The decrease of resistance that the cables undergo when entering the superconductive state and the decreased conductive loss due to the dielectric at liquid helium temperatures, closely approaches the functionality of an ideal cable (Allen, 1964).

Superconductive coaxial cables have the following advantages (Mikoshiba, 1976):

1) Large bandwidth capability from a few hertz to a few gigahertz.

2) Small physical size and low loss.

3) Low thermal noise due to the cryogenic environment.

4) Low crosstalk due to little penetration depth into the outer conductor.

2.1.1 What is a coaxial cable

Cables used for communication of electrical data including video, CATV, RF and microwave transmission. They consist of an inner pin or conductor, and outer conducting shield. These two conductors are separated by a dielectric material, usually Teflon or Polyethylene. They are transmission cables, used to carry high-frequency electrical signals with low losses. Figure 5 shows the cutaway of a regular coaxial cable which might or might not include a plastic jacket covering the metallic shield or outer conductor (Zhang, 2007). Regular coaxial cables have pins and metallic shields made out of copper which are usually rated to work between -55 to 200 Celcius (PIC Wire & Cable, ND).

It is important to mention that one of the main advantages of coaxial cables is that the dielectric material manages to contain the electrical and magnetic fields created by the push-pull of electrical signals, allowing for very little signal to leak, this also works the other way around not allowing noise to enter the cable. This makes coaxial cables ideal for scenarios where signals are weak and should not get interference from their surroundings (Kushino, 2018).

Coaxial cables used in quantum computing are made of superconductive material combinations like Niobium-Titanium or Silver plated Copper-Nickel and Teflon as the dielectric material (Coax Co, ND).

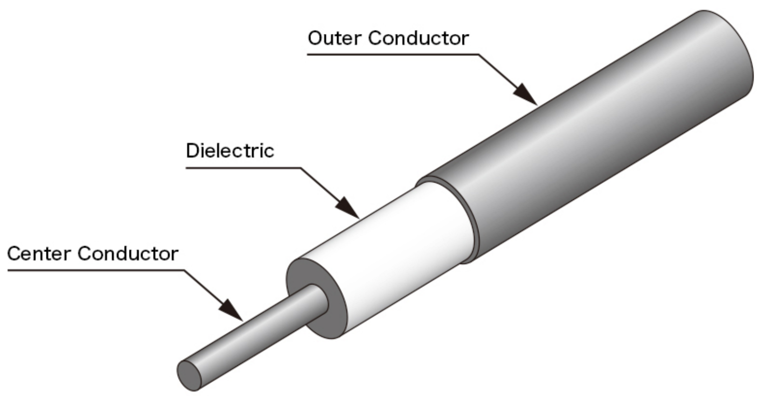


Figure 5. Coaxial cable (Coax Co, 2021)

2.1.2 Superconductivity

Certain materials demonstrate a set of physical properties known as superconductivity when they reach a critically cold enough temperature, the electrical resistance tends to zero and the magnetic flux field is eliminated from the materials, often called critical temperature. Usually the metallic conductor's resistance goes down as temperature goes down but it never disappears, except in the case of superconductive materials. This effect can only be described by quantum mechanics, which explains the complete expulsion of magnetic field currents from the inside of the superconductor at the critical temperature (Ginburg, 2004).

For the aim of this research the main superconductor used is Silver plated Copper-Nickel which turns superconductive at 10 Kelvin, these temperatures might seem extremely low and hard to achieve but they are no problem for the cryostat which cools down the lowest plate down to 0.01 Kelvin (Bluefors, ND).

2.1.3 Coaxial cables in Quantum Computing

These superconductive coaxial cables are used to communicate to and from the quantum chip, this is mainly because of the low power signals coming out and going into the chip. The low power used has two reasons, the first one is that outside noise and perturbations would get the qubits out of their superposition state which would destroy the experiment and the information held by the chip; the second reason is that higher electrical signals would bring with them energy which would translate to heat, which would heat up the quantum chip and would also ruin the superposition of the qubits, ruining the experiment (Razorbill, 2016).

Since the signals going in and coming out of the quantum chip are such high frequency and usually very weak, coaxial cables are the only viable cable to communicate with it. Another benefit of these superconductive coaxial cables is the extremely high rate of information that can be sent and received through them (Krinner,2019).

2.1.4 Requirements for superconductive coaxial cables

One of the main requirements for the coaxial cables when being used inside of the cryostat is for them to be able to resist the extreme thermal expansion and contraction of the repeated cooling cycles (Razorbill, 2016). This is achieved by bending the cables to the selected geometry discussed in chapter 3.3, which allows for the movement to be experienced by the cables without suffering any damage. The selected geometry, Figure 35, permits high packing density inside of the cryostat and allows the movement of the cables without them interfering with each other, it also lets the machine create the bends reliably and in a short amount of time.

2.1.5 Limitations of superconductive coaxial cables

When bending the cables or deciding the geometry for the cables it is important to keep in mind the physical limitations while bending, since too aggressive bending or too tight radiouses might; break the inside pin, damage the dielectric material, fracture the outside conductor or interfere with the signal (Coax Co, 2021).

Figure 6. Coaxial bent too aggressively, cracked outside conductor

Specifications from the manufacturer were kept in mind and the different geometries were thoroughly tested for any inconsistency in signals which would affect the functioning of the computer.

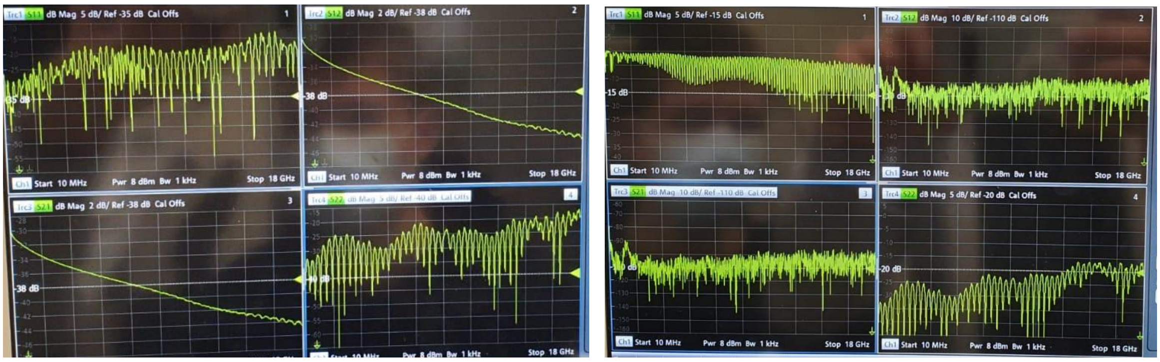


Figure 7. Correct signal (Left). Damaged inside pin (Right)

2.2 Commercial bending machines for thin cable

There are several thin cable bending machines available in the market, so it is important to mention requirements to reduce the available options to something that is easy to work with.

The following requirements are expected from the machine. These requirements have been determined by the customer demands. The ability to compensate for springback allows different materials to be used.

- Availability to work with cable diameter close to 0.8 mm.
- Accuracy of 0.1 millimeter in the feed.
- Accuracy of 0.5 degrees in bending radius.
- Possibility to compensate for springback.

Another very important requirement is that the cable needs to be bent by creating small continuous bends, this is required to not damage the coaxial cables, some machines bend the cable over a mandrel or push the cable against a pin which in turn creates the bend. The main issues with these two methods are that the mandrel only allows one shape to be made and the pushing method is hard or impossible with such a thin and delicate cable as the coaxials. On top of this, the mandrel bend tends to kink the wire which could change its characteristics and make the cables useless.

These requirements leave a couple good options and some questionable quality wholesaler machines which might not fulfill the promised capabilities and specs of the machine, these last ones will be ignored. Ideas from these machines were also considered and applied to the prototype in the design stage and for the postprocessing of the cable with an example being the Marshall cable magazine holder, which feeds one cable at a time and holds them aligned (Marshall, ND).

2.2.1 Pensa Labs D.I.Wire

Pensa Labs is a design company in the United States which offers a cable bending machine called D.I.Wire, this machine fulfills the previously mentioned requirements and also comes with a software that translates a 2D file into a finalized cable. The mentioned specs for the machine are as follows (PensaLabs, ND):

- Cable diameter: from 0.45 mm to 5.5 mm
- Bend accuracy: +/- 0.5°
- Feed accuracy: +/- 0.1 mm

This machine is compact and the mentioned reliability seems impressive for its cost, which is close to €18,000 (PensaLabs, ND). This is the closest competitor for the machine discussed in this research, but the following are the reasons it was decided to not purchase the D.I.Wire machine and instead build one from scratch.

It is meant to work with a roll of cable which feeds constantly through the machine and there is no solution for feeding sections of cable. The coaxial cables come in two meter sections which complicates the feeding, a specialized feeding machine needs to be constructed which was decided would be easier to do in a machine designed from scratch.

It has no solution to deal with the outcoming bent cables and a solution would have to be designed, manufactured and implemented, this is easier to do with a machine that has been built with that purpose in mind.

It is meant more for prototyping and testing bends or lengths, not so much for final production volumes, this is the main reason why this machine was not selected, since the required machine needs to be able to work long shifts without human intervention.

For these reasons it was decided to not buy the D.I.Wire, it seems to be a solid machine and the price seems fair for the promised specs, but the integration into the coaxial cables manufacturing would still require bespoke machines before and after it to make it work as needed. It is important to mention that the functionality of the prototype bender being tested is very similar to the D.I.Wire but it differs in that the focus of the prototype is only the coaxial cables, this reduces the need to design with several stock materials in mind, simplifying the machine and making it more focused on its purpose.

Figure 8. D.I.Wire Pro (PensaLabs, 2021)

2.2.2 Marshall CNC Wire Bender

Marshall Innovative Manufacturing Solutions has a cable bending machine which fulfills the requirements previously listed, the machine also has a cable feeder that deals with the two meter section coaxial cables, which improves the usability of the machine. It also has the possibility to separate the finished cables into different containers making it usable from beginning to end. This machine can work with small continuous bends or push bend which allows it to be used for the desired purpose (Marshall, 2021).

The downside of this machine is its sheer size, which makes the required space for manufacturing complicated. Another large problem is the way of holding the cable, it has a jaw that moves front and back and feeds the cable to the bending jig. This relies on the ability of the cable to hold itself, which semi rigid 0.86 millimeter coaxial cable can not do.

There are solutions offered by Marshall but it starts complicating things and it also reduces reliability.

The main issue with this machine is its lack of a cutter, it is meant to bend the whole cable and nothing else. The two meter coaxial cables usually produce five to eight cables, which would require a technician manually cutting the cables, reducing precision and increasing cost.

For all these reasons this machine was not selected as the solution for bending the coaxial cables.

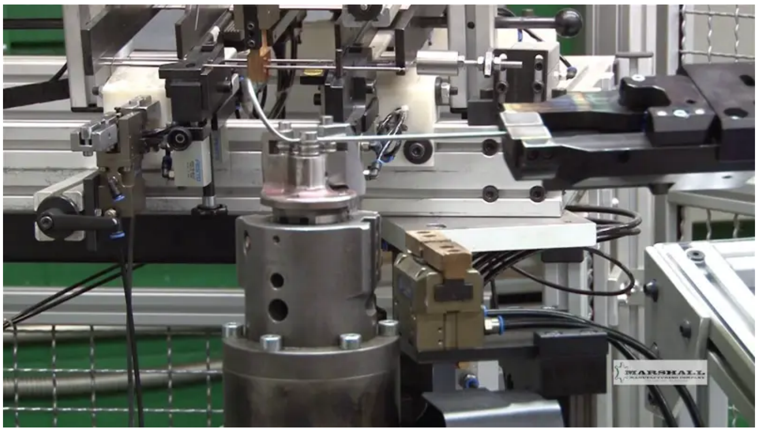


Figure 9. Marshall CNC Wire Bender (Marshall, 2021)

2.2.3 Stanley spring and stamping corporation

Another option available for bending thin round stock, are spring benders. These large machines have several heads to create different features in the stock. When the cable comes out it can be coiled, bent, formed and cutted with ease. The bends can be made by small continuous bends or bent over the mandrel.

This seems to be a promising machine for the required end product, which also matches the required machine specs and finished cable tolerances, with a minimum cable diameter of 0.2 mm (Stanley, 2021). But this does not come without issues. The size of the machine makes it hard to integrate into the production plant, and requires safety standards which elevate the cost of the manufacturing. It also requires more specialized technicians to operate it and requires constant maintenance.

This machine can not be left running on its own without technician supervision. It also has no solution for the two meter section cables or a solution for the outcoming cables. This complicates the application of this technology for the coaxial cables. On top of all of this, this machine has no method of avoiding marking the surface or scratching the cable since it is usually used with spring steel which is very tough.

Another option available is for Stanley Spring and Stamping Corporation to make the bending in house and then ship them to the required customer, the main issue here is the desire to make as many steps of the fabrication of the coaxial cables in house to keep a better quality control, eliminate lead time and ease of design change without an intermediary. For all these reasons this machine was also not chosen and the bending prototype was manufactured.

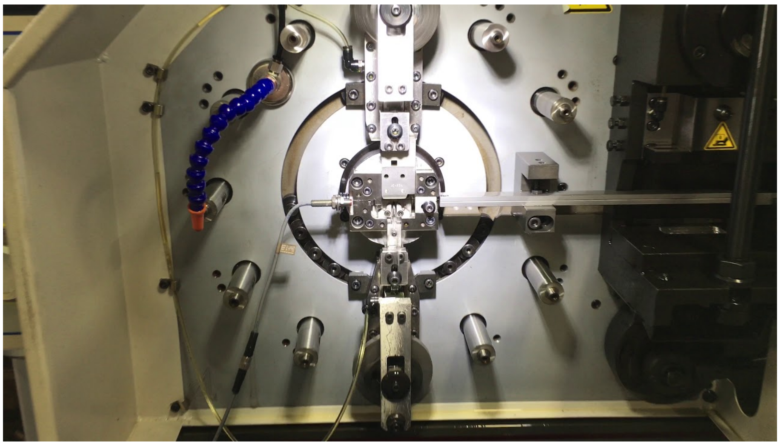


Figure 10. Stanley spring and stamping corporation (Stanley, 2021)

2.3 Patents for bending machines for thin cable

Patents show a great interest in thin cable bending since the industrial revolution when everything was mechanical and relied heavily on human interaction and crank powered gears. Times have changed drastically since those times and no importance will be given to old patents besides the historical value and the general idea, the following two patents were decided to have enough importance and similarity to the prototype bending machine to be included.

It is important to mention that the patents are mainly from the United States patent system for its ease of use and the language requirements, there are several patents in the Chinese patent service which could be integrated into this research but were left out for the complexity of the language and the lack of accurate enough translation tools.

The following patents encase the machines registered for this topic, since the bending mechanism is very similar in the machines from a century to a few years ago, the limitation to only select patents with motors controlling the motion was established. This reduces the amount of patents to be considered and it also makes them the most relevant for this research.

A brief explanation of the patent will be given and then similarities and differences will be addressed. Some ideas from these patented machines are very similar and other functions in completely different form.

2.3.1 Patent US20170312808A1

This patent shows a wire bending machine controlled by CNC and capable of translating .DXF files or .Step files into 2D bent cables, it functions with a gripper which pulls the cable through a series of straightener rollers to get rid of the stresses left by the cable being coiled. Then the cable is pushed by the same jaws through an opening which has a pin that rotates to both sides and gets bent by it. Inside of the opening there is a hydraulic cylinder which sheers the cable off when the bends are done.

This patent has similar functionalities to the prototype bender, for example the bending system is similar in that both have a pin which is capable of going up or down to change sides and it also bends with multiple continuous bending. It is interesting to see the utilization of hydraulics for the sheer and the gripping jaws. This allows the machine to be very reliable and for the forces to be very precisely controlled with good feedback, one problem with hydraulics is that machines using them require further certification to be turned into a final product and they also increase in complexity.

The simplified images show the main skeleton of the machine with the moving parts without components blocking the main parts. One of the differences which is clearly obvious is the fact that this bender works with cable that comes from a coil and it is very probable it would not be able to work with the two meter coaxial cables without having the waste get stuck while trying to pass it though the machine. There is also a limitation by how long the last cable can be because of the separation from the bending pin to the gripping jaws.

These two problems have been dealt with in the prototype by having two sets of blades and making the distance between the second feeling wheel and the bending pin smaller than the tail of the wires. The second blade is at the beginning of the machine and it only activates to trim off the waste from the two meter section, this allows the waste to never enter the machine eliminating the need to pass it through and avoiding jamming.

All and all this machine seems to be great for its intended purpose, and following the applicants name for the patent it takes us to a finished product which can be acquired and used for all sorts of bending applications.

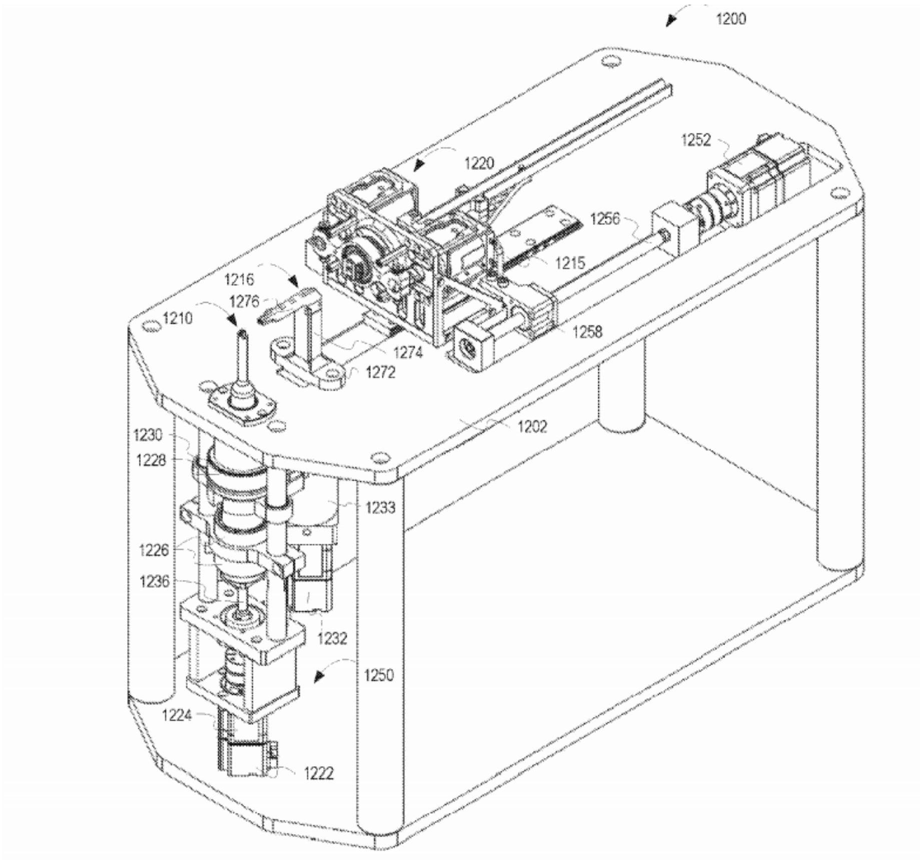


Figure 11. Esqueletal view of patent US20170312808A1 (Suto, 2017)

2.3.2 Patent US20200405452A1

This patent shows a bending machine for orthodontic wire that works in pair with a 3D scanner, which digitalizes the teeth of the patient and a program that translates that 3D model into the path the wire should take. It then translates that path into CNC language and bends the wire to fit. The method used to bend is very similar to the prototype as it has a bending pin which bends the wire against a form. The difference comes mainly in the feeding mechanism which has a timing belt used as tank tracks to hold the wire and push it outwards. This eliminates the feeding rollers and it also straightens the wire and keeps it straight while going through the machine.

Another characteristic of this bending machine is that the bending pin is not lowered but the whole assembly holding the bending pin is moved out of the way for it to be able to go to the other side. This creates the complication that the wire is not being held while the pin is changing sides and might create the problem of not straight bends which would need to be adjusted by hand by the technician using the machine. This seems to not be a big problem though, since the orthodontist will have to mold the wire to its perfect position anyway while gluing it to the teeth.

Another difference between this machine and the prototype is the way of cutting the cable once it is done, it has a diamond encrusted wheel which cuts the wire then it is ready. The prototype on the other hand uses electrical linear actuators to move a blade up and down, this was selected to not have to deal with metal dust after the diamond wheel has cutted the cable.

This shows that the main innovation available is in the feeding mechanism and it greatly depends on the cable being used. Several things need to be taken into consideration like the residual stresses in the cable or the shape it had before entering the machine. Also the stiffness plays a large role since the softer and more malleable it is, the more care has to be given to the handling. This is a problem with the coaxial since it is a soft casing, filled with soft dielectric material and a soft copper core. Also the outside of the cable cannot be marked by the feeding wheels, limiting the materials they can be made to anything softer than copper, like rubbers and soft polymers. These polymers have different limitations like the grip and the deformation they suffer when they grab the cables and push it through.

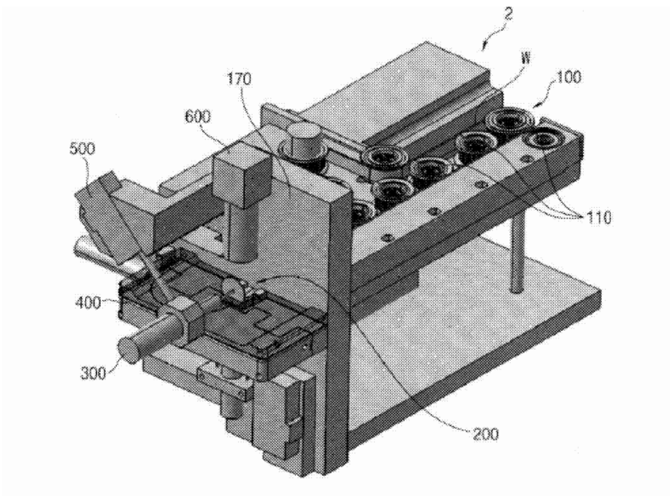


Figure 12. Inside view of patent US20200405452A1 (Song, 2020)

2.4 Methods to validate prototypes

Validation of the prototype is the main topic of this research, and therefore different methods were researched, this allows different focuses into the final product to be applied. Mainly the difference between the correct functionality of the machine and the quality of the final cable coming out of it. It is important to understand how these two factors are intertwined, since there cannot be good quality cables with a badly functioning machine, and a good functioning machine should never manufacture bad quality cables. The difference in validation methods selected for both scenarios is discussed in detail in chapter 3.5.2. Should be mentioned that most of the quality theories available focus on the management of an organization and not on the quality of a product on itself, these theories were quickly browsed through if they had any importance to the research.

2.4.1 Quality validation

Quality is the main focus of the validation method, for both the machine and the cables, but mainly focusing on the quality and variation of the final cables, specifically, the final quality of cables between each other (variation) and the final quality of the cables to the standard (deviation) since this talks directly to the correct functioning of the machine.

This topic has been discussed and analyzed since quality and precision started being a topic in manufacturing. Increasing the quality and precision of the machines fabricated allowed engineers to create more precise products, which in part helped make more precise machines. In any organization customer satisfaction is number one priority plus it directly translates to profit, and good quality and reliability serve this purpose (Taghizadegan, 2006). It can be said that today's technology is a testimony to man's incessant desire to provide a higher level of quality in products to increase market share and profits (Roy, 2010). Quality is more often than not essential; in health technologies, power generation, aerospace or even automotive bad quality can be deadly or extremely costly.

Quality has also been driven by the need to compete on price and performance, aiding companies to maintain profitability and scalability, by optimizing processes and products. On top of this, this quality surge would not be possible without the design of experiments theory behind it. Which helps define and investigate all the possible conditions in an experiment involving multiple factors, sometimes also referred as factorial design (Roy, 2010). Originally designed to understand the effects of different variables in the agricultural field, since it is hard to narrow down what is changing and it is also complicated to change only one variable. This leads perfectly into engineering, prototype testing and machinery validation since sometimes changing only one variable is complicated and in already built factories there are thousands of variables to consider.

The following are the methods considered to fulfill this purpose and aim to a high degree of quality in the final prototype and the manufactured cables.

2.4.2 Taguchi method

The taguchi Method is a methodology developed after World War II when the allies realized the bad quality and unreliability of japanese communication systems. They proposed the creation of a communications research facility and named Dr. Taguchi in charge of the R&D department (Roy, 2010). What came out of this is now known as the Taguchi philosophy, and has been adopted by large companies all around the world, its importance for the bending machine's quality control will be discussed in brief.

First the base ideas that form the taguchi method. These concepts are (Roy, 2010):

1. Quality should be designed into the product and not inspected into it.
2. Quality is best achieved by minimizing the deviation from the target. The product should be so designed that it is immune to uncontrollable environmental factors.
3. The cost of quality should be measured as a function of deviation from the standard, and the losses should be measured system-wide.

This mainly means that the quality should be planned and designed into the product and it should be made "noise proof", which means quality should always remain no matter the circumstances surrounding the manufacturing process. Variability in the ambient should not induce variability in the product. It also means that quality should be measured based on the standard, so deviation starts from a fixed point.

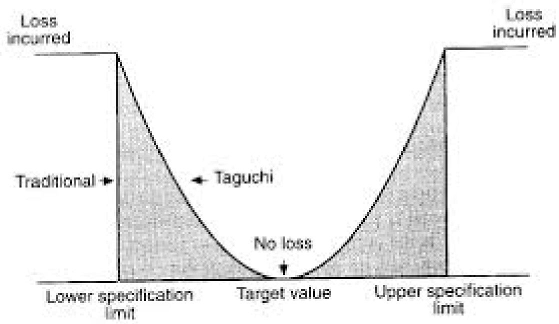


Figure 13. The taguchi methodology works towards no loss (Roy, 2010)

2.4.3 Design Of Experiments (DOE)

Experimentation is required to understand the manufacturing processes, they are conducted in tests which are meant to create quantifiable outcomes. For quality improvement to occur it is important to understand the process behaviour, the amount of variability and its impact on processes (Anthony, 2014). In the manufacturing industry, it is often desired to analyze the relationship between the main input variables and the output characteristics.

For example in the bending prototype the speed of the feed, the feed acceleration, the angle per bend, the sharpness of the cutters, etc. can be treated as input variables and the quality of the bend, the end radius of the bends, the final length, etc. can be considered as output performance characteristics.

A common approach in manufacturing is One-Variable-At-a-Time (OVAT), where only one variable is changed at a time and all the other variables are left as is. This way of testing depends upon guesswork, luck, experience and intuition for its success. These kinds of experiments use large amounts of resources and usually provide a limited amount of information about the process being tested, while also being sometimes unreliable, inefficient and it might also yield false optimum conditions for the process (Anthony, 2014). Nevertheless, it is still a valid method depending on the size of the experiment and the amount of times it needs to be repeated, which does not completely eliminate it as a possibility to test the prototype.

In designed experiments often changes in the input variables are done, and then how the output varies is determined. It is important to understand also that not all variables affect the output in the same way and this needs to be kept in mind. Some might have great influence and some might have none, therefore it is important to understand and calculate which variables should be changed for the expected result.

For the creation of a correct experiment to test prototypes the following steps should always be followed (Anthony, 2014):

1. Hyporesearch - an assumption that motivates the experiment.
2. Experiment - a series of tests conducted to investigate the hyporesearch.
3. Analysis - understanding the nature of data and performing statistical analysis of the collected data from the experiment.
4. Interpretation - understanding the results of the experimental analysis.
5. Conclusion - stating whether or not the original hyporesearch is true or false.

This methodology would function as the bridge between the proper functionality of the prototype and the final quality of the cable. The design of experiments would help create a link between the machine as an input and the cable as an output, while each of them also has their own validation process.

2.4.4 Process FMEA

Failure mode and effects analysis (FMEA) is the process of reviewing as many parts, systems and subassemblies as possible to identify the possible failure modes in an overall system and their effects and causes. Parts, their failure modes and their effects on the rest of the system are written down in a specific FMEA worksheet. The FMEA looked at here is the process specific FMEA or PFMEA, it is a methodology used to identify potential or expected processes failure modes and provide problem corrective actions (Przystupa, 2017).

The objective of the PFMEA is to identify and correct any failure modes before the first production run, this is usually applied to prototypes. When the failure modes are identified they should be ranked depending on their importance and danger to the final production, the most severe should be attended first. The PFMEA should be totally completed before the first production run (Stamatis, 2003).

One important step to fulfill the PFMEA is to understand the process to specific detail. The functionality of the prototype and the parts that form it should be understood and they should also be easy to visualize. It should be easy to answer the question, “What is the purpose of this operation?” and the answer should estate precisely what should be accomplished after the operation occurs. This helps divide the functions of each part or each assembly (Raghava, ND).

After this, a process flow diagram should be elaborated to more easily visualize what happens and when. This helps understand, agree and define the scope of the prototype. The way to go with the flow diagram is to ask what is happening in this step to the product. It maps what function is done by which part and in which order.

After the process is understood and mapped, the anticipated failure modes can be linked to the different processes by asking “How could this process fail to fulfill its purpose?”. This gives a general understanding of what to expect if a part or assembly fails. Which eliminates the guessing from the equation and makes the validation more reliable (Stamatis, 2003).

Following, this can be linked to the expected effect of the failure on the prototype, allowing a chart to be created linking machine failures to observed errors in the process. Some expected failures are: fatigue, jamming, improper torque being applied, overheating, slippage, inadequate clamping, inadequate bending, improper tension on belts, etc.

The frequency and severity of these failures should be estimated and should be written down in the PFMEA spreadsheet usually in values from 1 to 10, when 1 is not a severe consequence and 10 is the maximum.

The ideal scenario and the expected form of counteraction is to always prevent it from happening and that is one of the main purposes of the PFMEA. Recommending preventing actions is one of the sections that the PFMEA spreadsheet has as one of its most powerful tools (Przystupa, 2017).

The PFMEA method consists in determining the accurate numerical indicator to all parts in the device, followed by ordering the components according to the chance of failure. The FMEA is not meant to output, for example, the expected time between problems or failures, instead it is used to describe a type, effect, cause and severity of damage to the device which are defined by the risk priority number (RPN). A higher value of RPN, referring to specific elements, indicates the need to use preventive actions to improve the functionality and reliability of the prototype (Przystupa, 2017).

This is the best method available that fulfills the requirements for the validation of the prototype and also helps avoid mistakes in production, a modified version of this can be used to understand the quality and the failure modes that affect the quality of the final cable.

2.4.5 KPIs

Some KPIs that could be used to check the quality and quantity of the produced cables are (InsightSoftware, 2021):

Table 1. KPIs (InsightSoftware, 2021)

KPI	Focus	Formula (if applicable)
Cycle Time	Average time required to produce a single product. It is helpful when analysing the efficiency of a machine or production line.	-
Throughput	Measures the output capacity of the prototype compared with the expected numbers. This will help decide if the capabilities of the prototype are enough to fulfill demand or more machines would need to be manufactured. It is easily calculated when the cycle time is known.	-
Production Attainment	Calculates the percentage of time that target production levels are met.	Product Attainment = (Operational Time Meeting Targets / Total Operational Time) * 100
Avoided Cost	Estimates how much money is saved by spending money. For example, how much equipment maintenance costs were vs. how much repairs would cost if the machine broke down, plus lost production revenue.	-
Machine Downtime Rate	Measures the amount of downtime a machine has, be it scheduled or unscheduled.	Machine Downtime Rate = ((Scheduled Downtime + Unscheduled Downtime) / Total Time) * 100
Percentage Planned Maintenance	Ratio of scheduled maintenance vs. unscheduled maintenance. It is useful in identifying assets that require more preventive maintenance.	Percentage Planned Maintenance = (Planned Maintenance Hours / Total Maintenance Hours) * 100
Downtime to Operating Time	Measures the downtime compared to the operating time.	-
Capacity Utilization	Determines the production capacity being utilized as a function of total production capacity.	Capacity Utilization = (Actual Output / Max Possible Output) * 100
First Pass Yield	Measures how many products produced meet specification on the first quality control inspection.	First Pass Yield = (# of Units That Pass Inspection the First Time / Total # Units Produced) * 100

These metrics could be used hand in hand with the verification method to validate the efficiency and quality of the final production.

3 Material and methods

This chapter focuses on the experiments done to complete the validation of the prototype and the methods used for it. It goes into detail on the prototype and its functionality, the parts that comprise it and how they affect the final cable. Aso, all the instrumentation created for the validation and its correct utilization.

3.1 Bending prototype

The main function of the bending prototype is to measure, bend and cut the cables to the different required lengths, this is currently done by experienced technicians, usually micromechanics or watchmakers, since the tolerances are small and require great precision for the final signal of the cable to be reliable.

3.1.1 Basic functionality

The prototype functionality is divided into three parts.

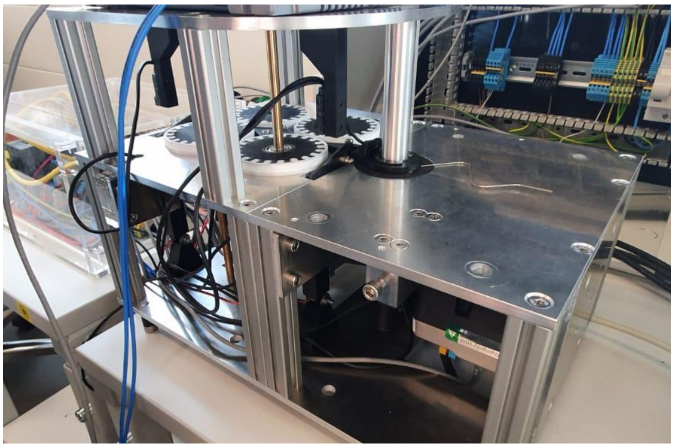


Figure 14. General view

The first main part involves the feeding of the cables in and out of the machine. This is accomplished with two pairs of wheels which oppose each other. The wheels have a TPU 95A 3D printed tire around them to increase the grip without damaging the cable. Each pair of wheels, A-B and C-D, turn in opposite directions. Rotation is synchronized by a gear connecting both as seen in Figure 16. The rotation is controlled by the stepper motors 1 and 2 which are solidly attached to wheel A and C. Wheels B and D are free spinning and kept in place by vertical shafts a and b.

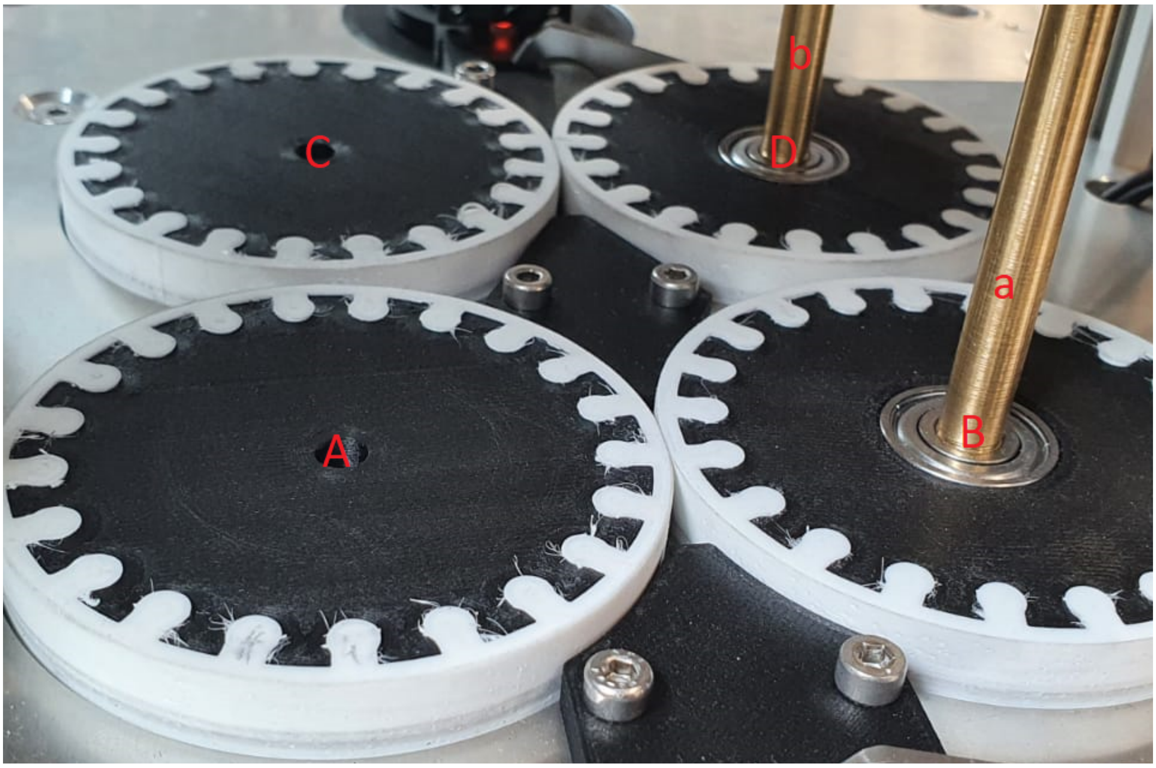


Figure 15. Feeding wheels

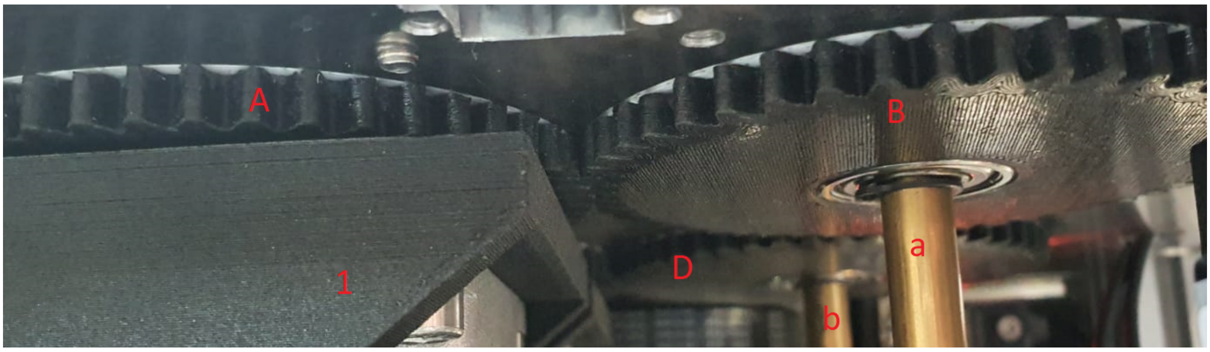


Figure 16. Gears in feeding wheels

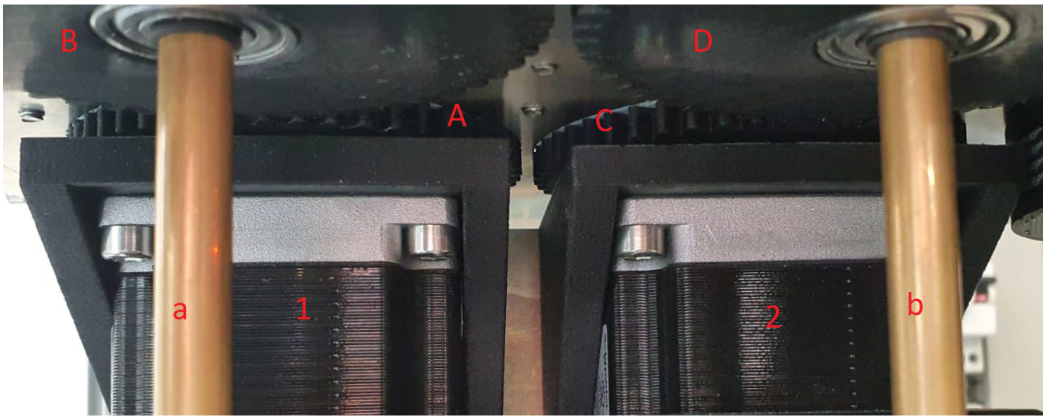


Figure 17. Feeding stepper motors

The second main part in the machine is the cutting of the cable once in the correct position and the correct length. This needs to be separated into two parts again. The measuring and the cutting.

Part 2.1, measuring, is done with two infrared sensors. Sensor 1 detects when the cable enters the back of the machine, Figure 18. This allows the machine to begin the cycle, setting in motion the feeding wheels until the tip of the cable reaches Sensor 2, Figure 19 which zeros the machine. At this moment the position of the tip of the cable is known and allows for precise measuring counting the steps taken by the stepper motors.

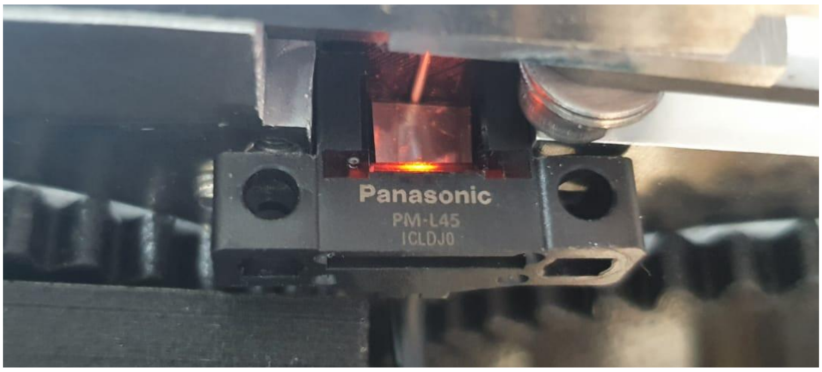


Figure 18. IR sensor 1 in the rear

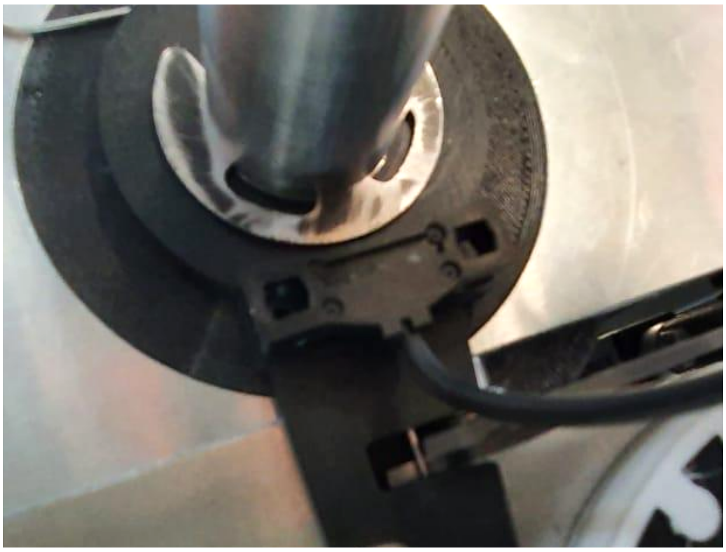


Figure 19. IR sensor 2 in the front

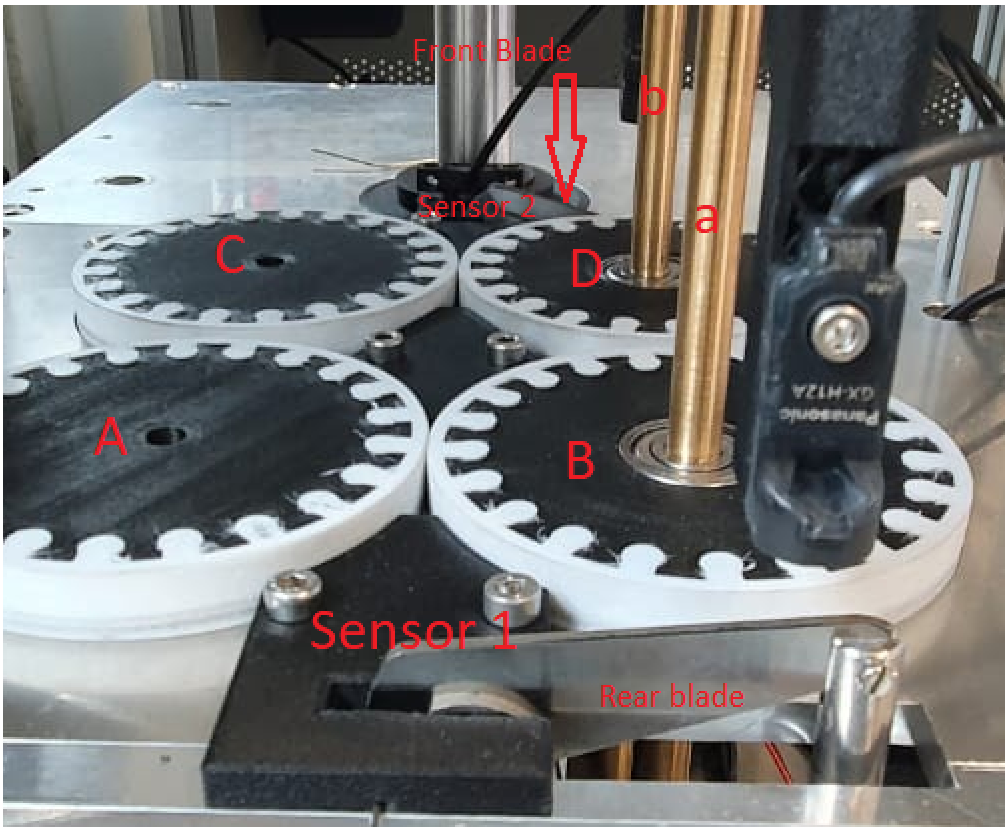


Figure 20. Full top view

Part 2.2, cutting, is done after the exact position is known. This is accomplished by two blades. The rear blade gets rid of the waste and does not allow it to enter the machine, since as previously discussed the cable comes in two meter sections and there is always some mm of waste at the end. The front blade is the one that does the main cutting, splitting the completed cables from the main length. These blades are actuated by an electric linear actuator which raises and lowers them.

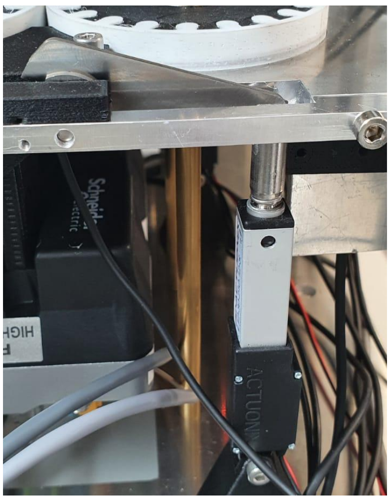


Figure 21. Linear actuator for blades

The third main part could be considered the main functionality, it consists of the bending of the cable. This is accomplished by a pin, Figure 22, which rotates around shaft c, it's important to notice that shaft c also works as the holder and output of the cable. The rotating pin pinches the cable against the bending ring and bends it the desired amount of degrees. After a bend has been done to one direction the pin is retracted under the table and taken to the other side of the cable, where it will repeat the process bending the cable to the other direction this time. This allows the machine to create different shapes and radiouses by varying the degrees bent by the pin and the lengths fed between bends.

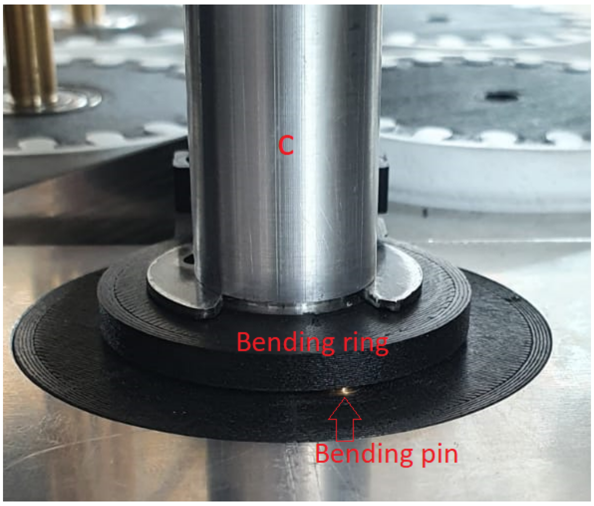


Figure 22. Bending assembly

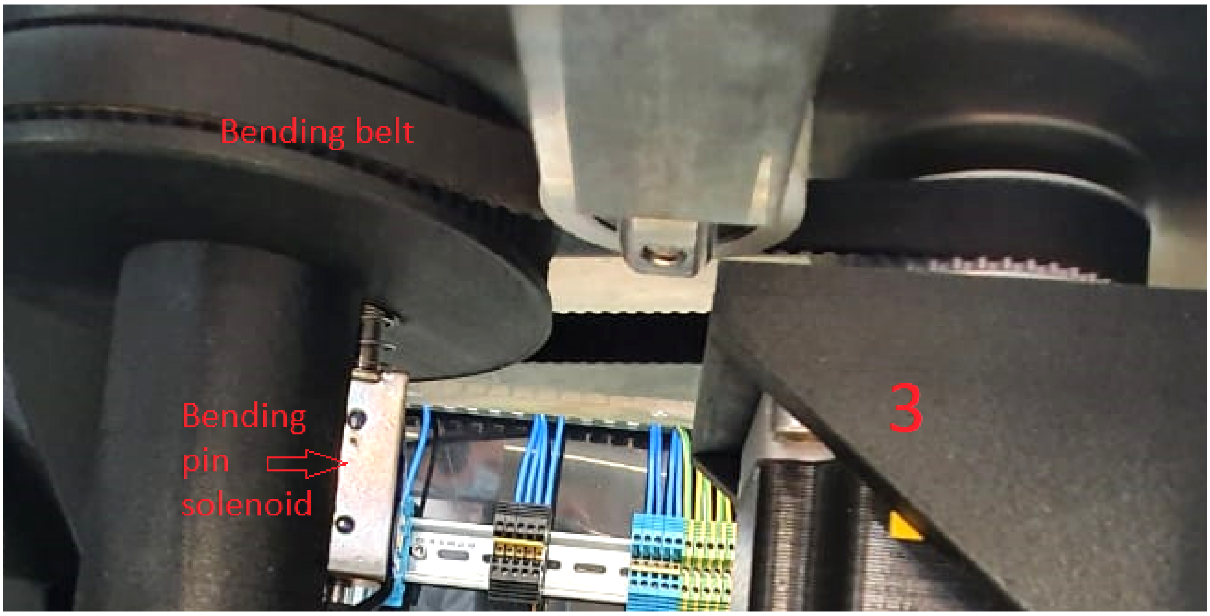


Figure 23. Bending stepper and belt

When the cable is bent and cutted it is pushed out by the incoming next cable and then a technician can sort them into different bins depending on their length.

3.1.2 3D printed parts

3D printing played an important part in the design and the manufacturing of the machine, it was decided that the main wheels and pulleys would be printed with a PA12 + CF15 carbon fiber reinforced nylon. This material has a high toughness value (125 MPa / ISO 527), is lighter than aluminum and it can withstand the forces and demands of an industrial machine. It also has high heat resistance which allows the stepper holders to not deform and stay rigid even under demanding conditions. The feeding tires are also printed in TPU 95A which allows flexibility in their design focusing on more or less grip. Figure 24 shows the PA12 + CF15 feeding wheels and TPU 95A tires.

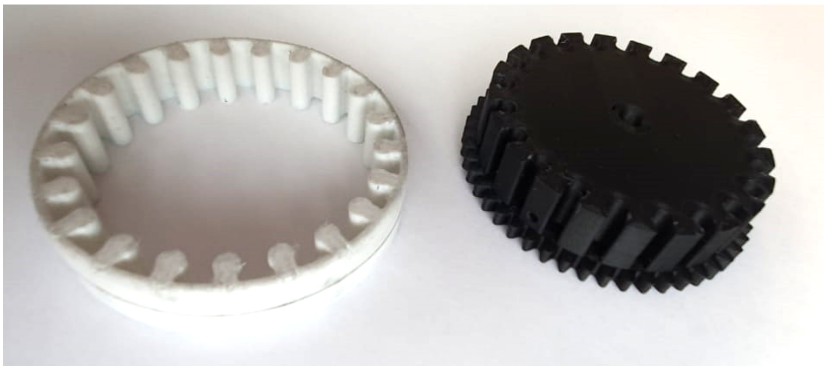


Figure 24. Feeding wheel and tire

On top of all of this, the flexibility provided by 3D printing in prototype iteration cannot be understated. It also allows complex parts to be easily manufactured and it allows the manufacturing of custom parts that can accomplish more than one task when compared to off the shelf parts. It also allows the project to be scaled up by simply printing more of the same part at an extremely low cost.

3.1.3 Sensors

Table 2. Sensors

Inductive sensors: Panasonic GX-H12A.	 Figure 25

Inductive sensor: OMRON E2B-M12LS04-M1-C1	 Figure 26
IR sensors: Light gate panasonic PM-L45	 Figure 27

3.1.4 Actuators

All the motion required in the machine is done by actuators which include:

Table 3. Actuators

Stepper motors: LMHCE572	 Figure 28
Linear actuator: Actuonix Micro Linear Actuator	 Figure 29

3.2 PLC controller

A programmable logic controller is an industrial digital computer, made specifically for the hard and demanding environments of manufacturing processes, such as assembly lines. They are extremely reliable which allow them to control large heavy machinery. They are easy to program and they have advanced fault detection systems.

All of this makes the PLC an ideal control computer for the bending prototype; they can vary from small modular devices with a processor and a few I/O pins to large interconnected modular devices with thousands of I/O pins.

PLC systems are immune to temperature changes, electrical noise, vibration, impacts, etc. and the program is usually stored in a battery powered non volatile memory.

A Siemens PLC was selected for this prototype because of its ease of use and easy integration with already existing systems. It is also easily expandable and can accommodate future stages of the bending machine or several machines at the same time.

3.2.1 Main components

The main components in the selected PLC are as follow:

Table 4. Main component list

Power supply for cpu: PM1207 6EP1332-1SH71.
Power supply for stepper motors: SITOP PSU200M 6EP1334-3BA10.
CPU: 1214FC DC/DC/DC 6ES7 214-1AF40-0XB0 Firmware V4.3.
I/O modules: SM 1226 F-DI8/16 x 24VDC 6ES7 226-6BA32-0XB0.
HMI screen: KTP700 Basic PN 6AC2 123-2GB03-0AX0.

3.2.2 Software

Two different softwares are required for the correct function of the PLC and for an easy integration with the bending prototype. They are:

- Siemens TIA portal: Totally Integrated Automation Portal (TIA Portal) is a program created by Siemens and meant to provide the interface between the PLC controller and the programmer. It gives access to digital automation services, digital planning, integrated engineering and transparent operation. It has integrated simulation and tutorials (Siemens, ND).

- Lexium MDrive: Is the required software for the MDrive stepper motors from Schneider, they integrate the motor, driver, controller, internal encoder and closed-loop performance. Units are programmable and networkable, which allows the motion control requirements of the prototype (Schnider electric, ND).

3.2.3 Programming

This research was done in parallel with research “Program design and automation of device for bending coaxial cables” by student of Automation Engineer Toni Berg at Metropolia University of Applied Sciences, the research goes into detail on the programming and PLC system. The programming and validation was also done hand in hand with Toni Berg since his input was of the utmost value to this research.

3.2.4 Main variables for tuning

The main variables in charge of the control of the movement in the machine and which have the greatest effect in the behaviour of the cable inside the machine are the Feed and the Bend variables. They control the number of steps the stepper motor should move to bend or feed the cable forward. As previously mentioned the prototype bends the cable with a continuous bending motion which means there are tiny bends followed by tiny feeds and this allows a continuous curve to be applied to the cable. Hand in hand with these variables is the amount of bend/feed cycles required to achieve the required radius.

These variables will be tweaked to ensure the cable has the expected geometry:

- Feed steps
- Bend steps
- Amount of Bend/Feed cycles

3.3 Instrumentation and materials

3.3.1 Cable substitute

As previously stated, the coaxial cable is very expensive and not worth doing the rough experiments with it. So a substitute was selected and tested to prove that the behaviour is similar.

There is a list of requirements that would validate if the cable is appropriate or not, before even testing the force and springback. The thickness of the cable needs to be +/- 5% of the coaxial cable since a thicker cable would not even fit through the machine. The cable cannot have an insulating cover since it would be too different. The cable can be plated but it cannot be plated with soft or toxic materials, like lead.

An apparatus was constructed, Figure 31, which allows the cable to be held in a firm and repeatable way, then a force was applied to the cable in a very specific place. The measurement of the force would tell us if the cable is similar in behaviour and springback and if it would be a good substitute. Table 5 shows the different cables that were tested and the results of the tests. Since the only important thing is the relation between cable behaviour, there are no units for the force measured.

Table 5. Wire substitute comparison

Cable material	Cable diameter (mm)	Force measured	Springback
SCuNi-CuNi coax	0.86	6 lines	17.5 degrees
Sn plated Cu	0.90	6 lines	13.5 degrees
Cu welding rod	0.92	12 lines	27.5 degrees
AL welding rod	0.90	3 lines	3 degrees

Figure 30. Different cables

It is clear the most similar cable to do the testing with is the Sn plated Cu (SnCu) even though it has different springback rates. This is not a real problem since the code has a variable for springback which takes it into consideration and allows a seamless change from SnCu to SCuNi.

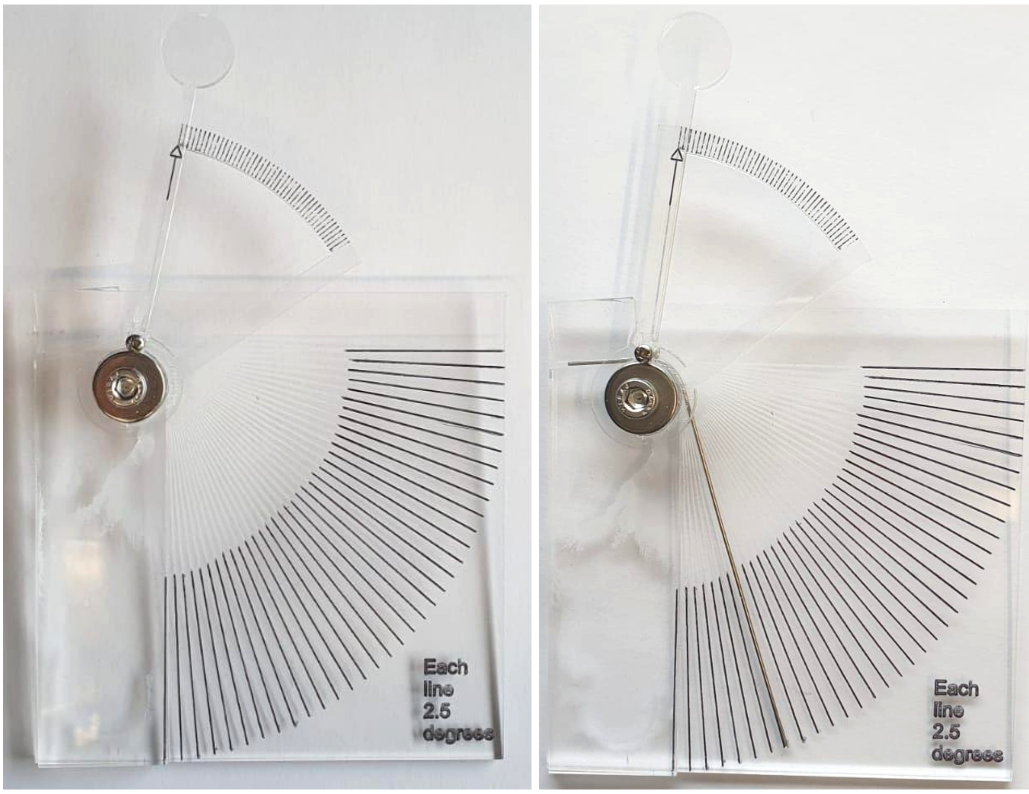


Figure 31. Force testing apparatus (left). Example springback in SCuNi (right)

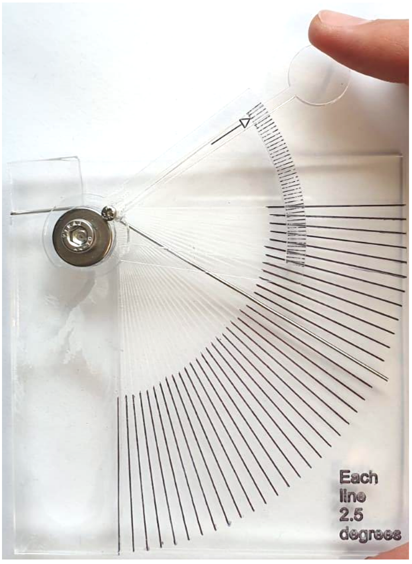


Figure 32. Example force measured in Al (frame taken from video)

3.3.2 Cable geometry

As mentioned in the introduction, the old geometry of the cables ment they created heat by friction rubbing against each other and to avoid this a cotton thread was used to tie a knot between the touching portions, which was extremely slow to manufacture. To remedy this situation and to improve the density of cable packing in the system a redesign of the whole geometry was experimented with, figure 33 and 34 show the different iterations tried which can be divided into two dimensional and three dimensional. The three dimensional cables create a lot of benefits but also several big problems, like the need for a three dimensional machine and three dimensional cable packing which is not as efficient as two dimensions, this means cables E and F were discarded.

The rest of the wires were eliminated as follows. D has no benefit for the packing and the 120 degree bend makes it complicated to manufacture. C has too many bends which complicate the manufacturing and bring no benefit. B has too little bends which causes the wire to move sideways under tension requiring more free space around the wires. A has the benefits of moving linearly under tension and the best packing capabilities so this geometry was chosen.

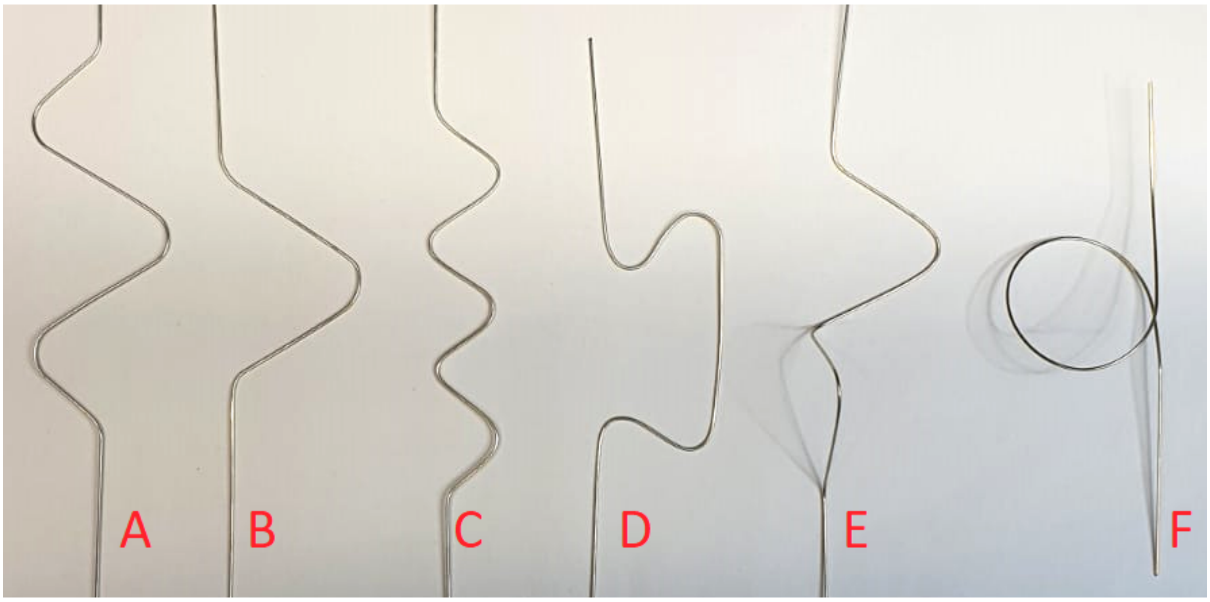


Figure 33. Different cable bending iterations.

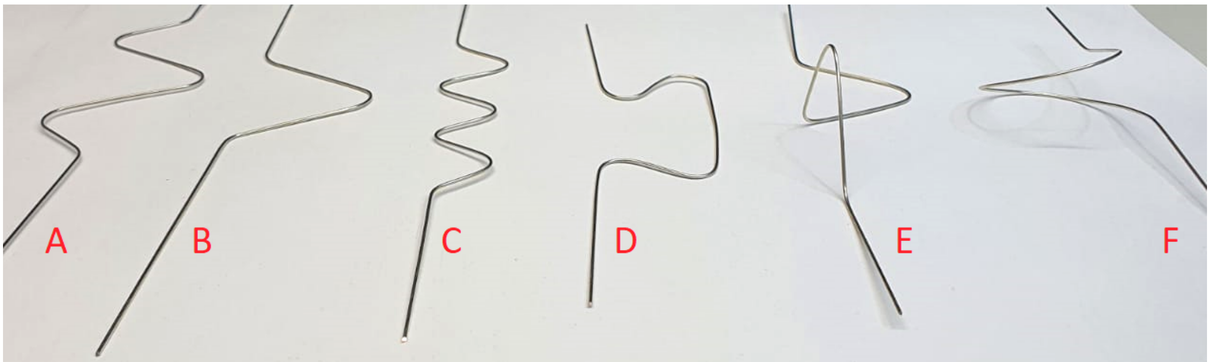


Figure 34. Different cable bending iterations showing third dimension.

Figure 35 shows A the selected zigzag geometry. This geometry not only completely gets rid of the cotton knot problem but also allows for a dramatic increase in the packing density, allowing the new high-density flanges to hold three times as many cables as the older largest flange. It also deals with the problem of thermal strain relief and it allows the bending machine in question to manufacture them in a fully automated way.

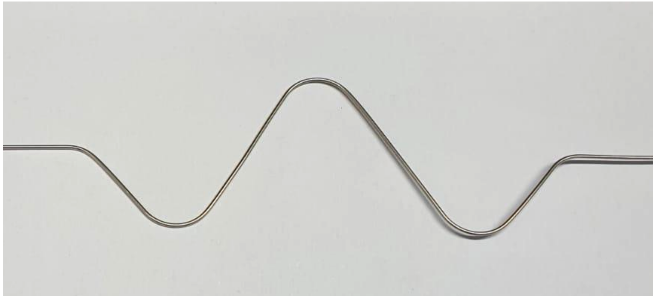


Figure 35. Selected geometry for coaxial cable.

3.3.3 Go-NoGo gauges

The following gauges were used with the method Go-NoGo for quality control. They help quickly and visually check if the finished cable accomplishes the quality requirements. The main attributes from the final cable were considered and translated into the gauges. The first, figure 36, is a very simple and practical acrylic jig that was laser cut, engraved and painted, it contains all the bends and the straight parts of the cable, it has marks where the bends should start and end and the correct radius. The second gauge, figure 37, is made to check the length of the final cables, it has marks in all the final lengths so it works for all the cables the prototype is expected to manufacture.

These jigs will be useful in the tuning of the machine but they will also be kept for the manufacturing process, where after every X cables have been manufactured a quality control check can be done. X cables will be tested at random and the machine will be allowed to proceed if the quality is under control, if not a round of tuning should be done.

Figure 36. First jig

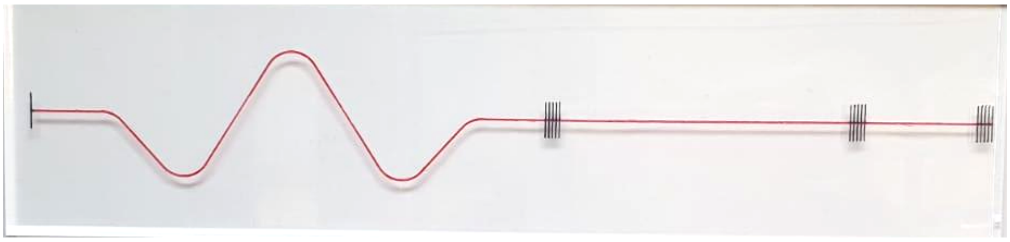


Figure 37. Second jig

3.4 Tests and experiments

The following tests were done to understand what the effect of moving one of the variables does to the cable when being processed while maintaining all the other variables the same, which is an idea taken from DOE theory. This helps get a quick idea of what might be wrong when tuning, it makes it easier to quickly know which variable needs to be tweaked to correct the problem. The experiments exaggerate the offset of the desired variable so the effect can also be magnified.

The three variables were considered here, the feed while bending, the bending angle of each bend and the amount of cycles. First, the feed between bend steps was doubled and the cable can be seen in figure 38. It can be noted that the radius and the arc get halved. Second, the feed between bend steps was doubled, while the bending angle was kept the same, the result can be seen in figure 39. It can be noted that the length of the arc and the radius double in size. Third the amount of cycles was doubled and the result can be seen in Figure 40.

Figure 38. Double bend steps.

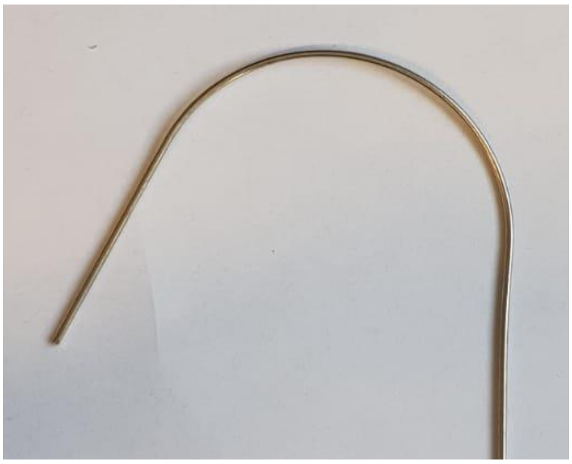


Figure 39. Double interbend feed steps.

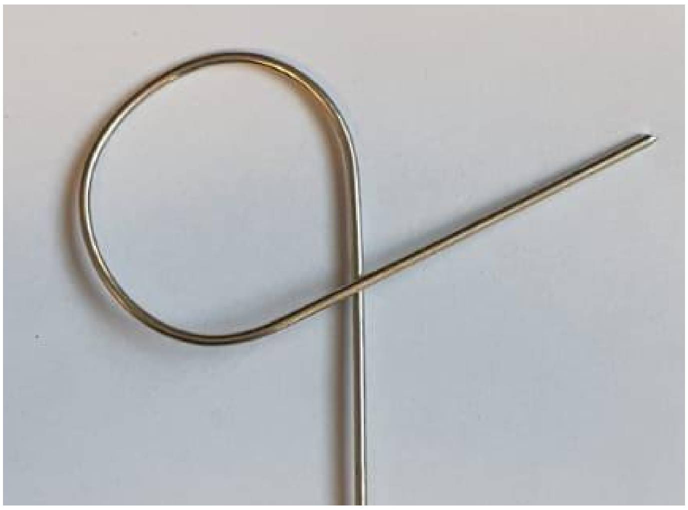


Figure 40. Double bending cycles.

This gives a clear indication on what variables to tune depending on the characteristics of the finished cable. Also the gauges can be really useful at this point. It is easy to see how these two tools facilitate defining what variable to change and by how much to change it.

3.5 Validation

3.5.1 Jigs validation variables

The jigs are connected to the variables in the code with the experiments done previously, notations were made next to the jigs for easy understanding of errors. It is now easy to observe the cable in the jig and see which part of the red underlying line shows up and quickly link it to the variable in the code that could correct it. All of these parts connect flawlessly in the way they help each other validate the code and its connection with the output cable.

3.5.2 Selected method

The way the validation of the prototype and the final produced cable quality went, is as follows:

1. PFMEA is done for the prototype, which helps understand the parts and subassemblies, their functionality and their tendency to fail. This provides the PFMEA spreadsheet which makes the testing and tweaking easier and gives an overview of the process in clear terms. This creates a sturdy machine that is less prone to failure and reduces downtime.

2. A tuning validation cycle is done for the cable, this divides the different parts that constitute the cable and the mechanisms that create the characteristics of the finished cable. It makes it easy to understand which components change which parts of the cable. This gives the opportunity to tweak and calibrate the machine in conjunction with the machine PFMEA.

The efficiency of this prototype will help push the manufacturing of the coaxial cables into the mass quantities, where the prototype will become an essential part of the production line and will begin paying for its own research and development and start creating a profit.

It is important to also mention why the rest of the methods were not selected. The taguchi method would be excellent in a scenario where the prototype was still in the design stage since its main focus is quality of machinery and production. Since the prototype has already been built and the quality needs to be achieved by tweaking the program that controls it and the variation in the already manufactured parts it will not be used but the theory will be kept in mind.

The KPIs are out of the scope of this research since the prototype did not enter full production and the actual full production values were not evaluated. This makes the main parts of the KPIs not relevant for this specific research, it also means that for the next steps after this research is finished it is the strongest tool available. DOE is a very valid method which would be valuable for the validation but the PFMEA simply approaches the desired qualities more, and evaluating with DOE and PFMEA would mean reworking several processes.

3.5.3 PFMEA method for prototype

The prototype was assembled and connected to the PLC controller, which had a test program that was expected to produce a geometry close enough to begin test trials. Figure 41 shows the first cable to come out from the machine, which has several obvious problems. To understand the problems the following process flow diagram, figure 42, was used to write the PFMEA worksheet, figure 43. PFMEA worksheets are usually used to understand the failure that the parts can experiment while the machine is functioning at production pace, but in this instance the PFMEA focuses in the failure modes caused to the quality of the cable by each of the components and it helped visualize what effect each part can have when it wears down or loosens.

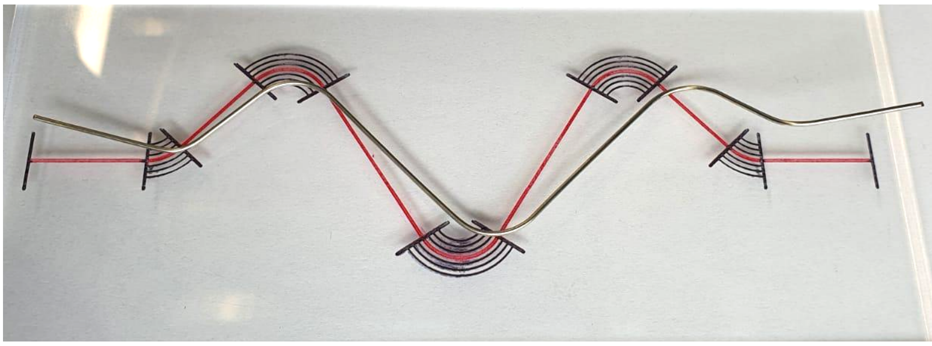


Figure 41. First wire.

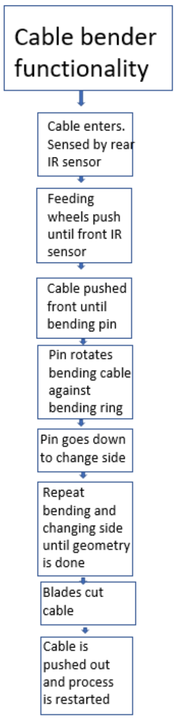


Figure 42. Process flow diagram.

As previously mentioned the process flow diagram is used to follow the process taking place and deciding the elements of the prototype that are being utilized. This helps understand and point to the correct parts for each process. The following PFMEA was made by carefully analyzing the effect of the parts charted in the cable, focusing on the three following characteristics: probability of failure occurring, severity of the failure and detectability of the failure. These characteristics are graded from one to ten and the product of them is written into the relative weight of the failure column, aiding the identification of the most severe failures, this is extremely helpful in tight schedule scenarios since only the top failures could be dealt with and the risk would stay low.

System: Cable bending Prototype							
Number	Element	Potential failure	Potential failure effect	Probability of failure occurring	Severity of the failure	Detectability of the failure	Relative weight of the failure
1	Rear sensor	Not sensing	Machine cycle does not start	4	1	1	4
2	Rear sensor	False sensing	Machine cycle randomly starts	1	1	1	1
3	Feeding wheels	Slipping in the shaft	Short cables manufactured	2	9	10	180
4	Feeding wheels	Non concentric to shaft	Slippage, which can cause short cables to be manufactured	1	9	10	90
5	Feeding wheels	Not perpendicular to shaft	Coiling of the cable	1	9	3	27
6	Feeding wheels	Not round	Slippage, which can cause short cables to be manufactured	3	9	10	270
7	Feeding tires	Inconsistencies in infill can create slippage	Slippage can cause short cables to be manufactured	3	10	9	270
8	Feeding tires	Printing layer change creates bumps	Clamping the cable too hard or too loose	4	9	1	36
9	Feeding tires	Not round	Slippage, which can cause short cables to be manufactured	3	9	10	270
10	Front sensor	Not sensing the tip of the cable correctly	Short or long initial feed	4	10	9	360
11	Front sensor	Random sensing	Sequence cancels	2	8	1	16

12	Bending ring	Wear in the bending radious	Different geometry as more cables are manufactured	4	9	7	252
13	Bending pin actuator	Getting stuck up	Catastrophic failure expected	5	10	6	300
14	Bending pin actuator	Getting stuck down	No bending happening	5	2	2	20
15	Bending pin belt	Slack creates imprecise bends	No bend would look the same, hard to track down with code	4	10	8	320
16	Bending pin belt	Belt breaks	No bending happening	1	2	2	4
17	Blades	Loose blades	Uneven cut would affect fit in bending ring, jamming the prototype	3	10	1	30
18	Blades	Dull blades	Uneven cut would affect fit in bending ring, jamming the prototype	3	10	1	30
19	Cable anticoil plate	Too tight to the bed	Limits the motion of the cable modifying its geometry	1	8	1	8
20	Cable guides	Worn	Slack in the guides prevent sensor from working properly	2	7	7	98
21	Cable guides	Missaligned	Coils cable and damages surface	7	9	2	126

Figure 43. PFMEA worksheet used to validate proptypes by understanding the process, finding possible failures and solving them.

The PFMEA is clear on what needs to be addressed before the prototype can go into production, everything above 100 has been marked in red for easy visualization. The order of problems to be solved are as follows:

1. Feeding wheels slipping in the shaft
2. Feeding wheels not round
3. Feeding tires infill inconsistency
4. Feeding tires not round
5. Front sensor not sensing
6. Bending ring wear
7. Bending pin actuator getting stuck up
8. Bending pin belt slack
9. Misaligned cable guides

After each problem has been figured out a test cable will be analysed and the improvements checked.

4 Results

The results are presented in the following sub-chapters focused on the solution to the PFMEA and the research question established at the beginning of this document.

4.1 Results from cable quality validation

Figure 44 shows a bent cable done with the original temporary tune after the prototype PFMEA process, the main problems have stopped and the focus goes mainly into the geometry. The gauges were used one by one to tune the different bends and lengths. The cable will be divided as shown in figure 45 (expected geometry) for easier identification of its characteristics. It is important to mention that there are equal lengths and bends in the geometry and they will be denoted with the same letter.

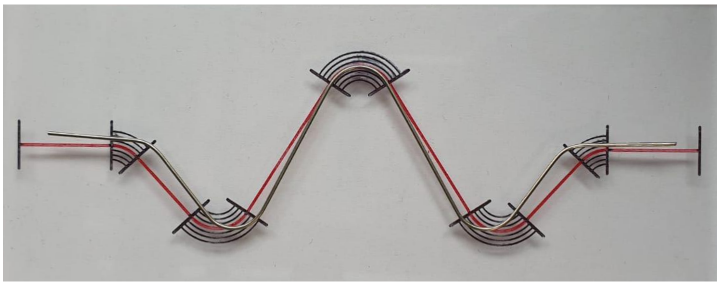


Figure 44. First cable after PFMEA.

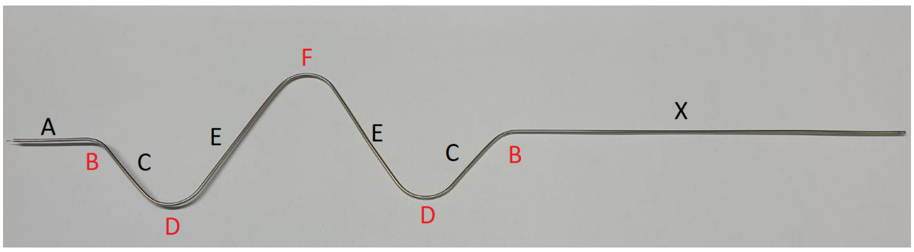
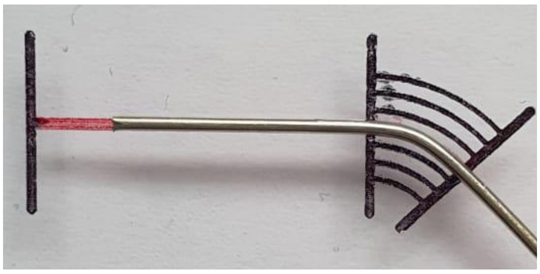
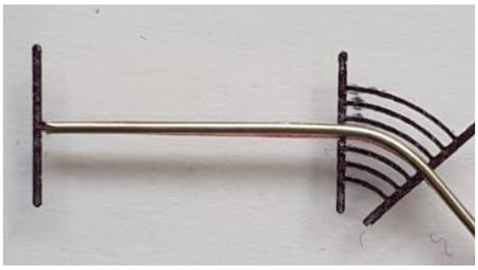
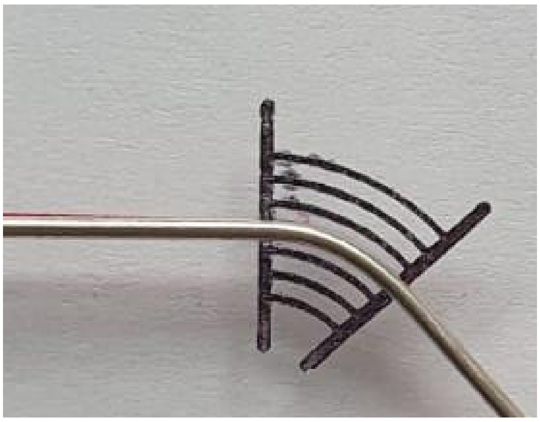
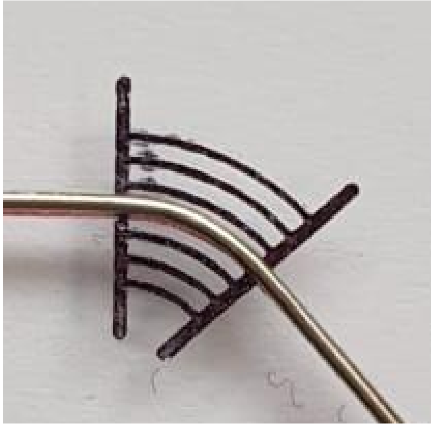
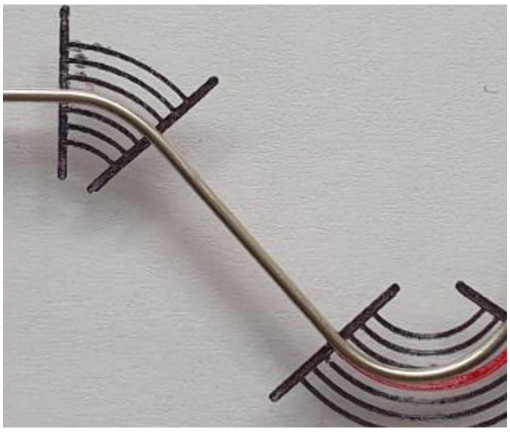
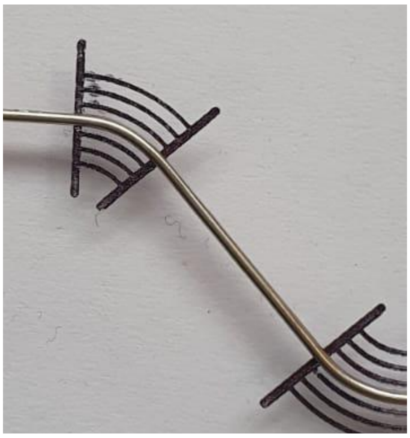
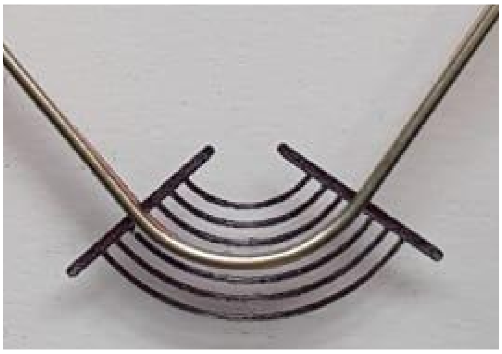
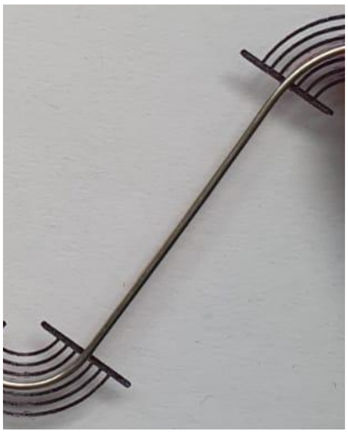
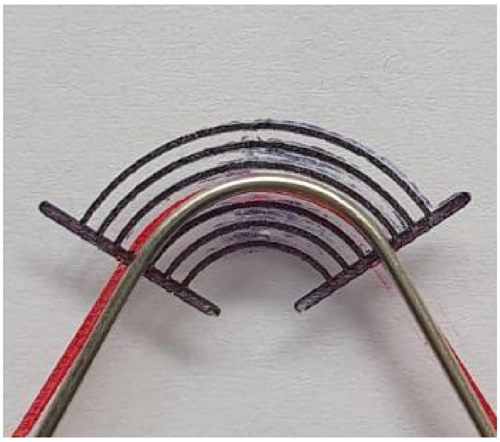
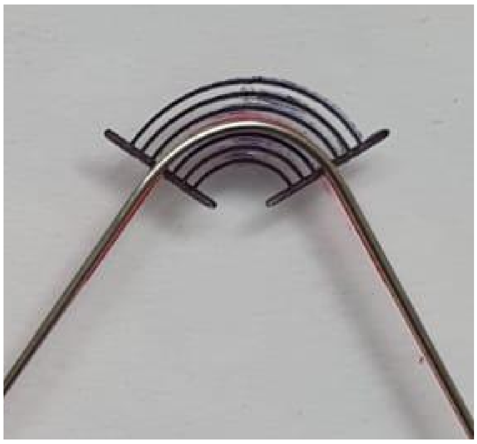
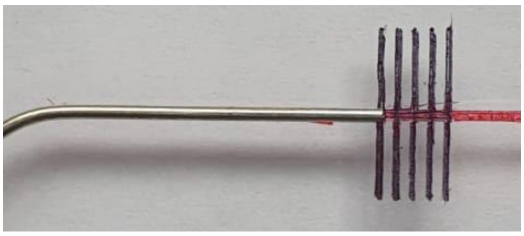
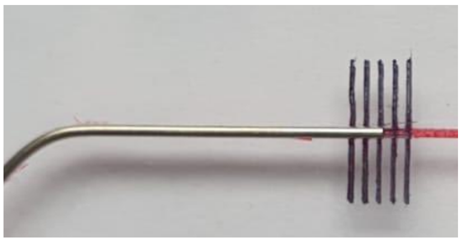


Figure 45. Cable geometry division (expected geometry)

Table 6. Tuning results

	Original tune in gauge with original values	Final tune in gauge with final values
A	 Feed steps: 4300	 Feed steps: 7471
B	 Bend steps: 1100 Interbend feed steps: 100 Cycles: 5	 Bend steps: 1250 Interbend feed steps: 106 Cycles: 6
C	 Feed steps: 1800	 Feed steps: 1908

D	 Bend steps: 1100 Interbend feed steps: 100 Cycles:15	 Bend steps: 1250 Interbend feed steps: 106 Cycles: 13
E	 Feed steps: 3600	 Feed steps: 3738
F	 Bend steps: 1100 Interbend feed steps: 100 Cycles: 15	 Bend steps: 1250 Interbend feed steps: 106 Cycles: 14
X	 Feed steps: 7000	 Feed steps: 7596

It is important to mention that this calibration was done with hundreds of cables but only the initial and final cables and values are shown here.

Figure 46. Test cables SnCu

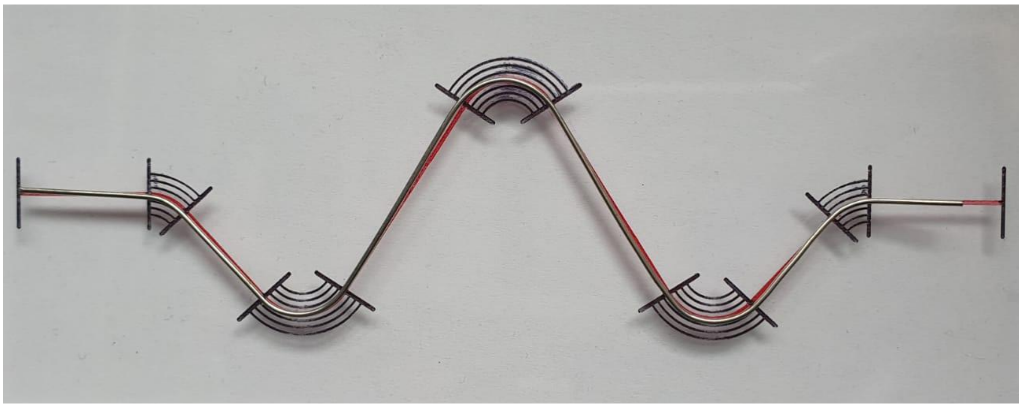


Figure 47. Cable after tuning

4.2 Results of validation for SCuNi cables

SCuNi cables have to be tried in the machine as a final test of its quality, the springback difference was applied to the code as a multiplier variable which changes all the code to work with SCuNi by only activating it. The results required a slight tune of said variable since the calculation ignores or assumes several factors which would be too complicated to calculate and relatively easy to get right by trial and error.

The first coaxial that went through the machine can be seen in figure 48, and the different trial and errors approaching the correct geometry are shown in figure 49. This form of tuning the code to match the requirements of the SCuNi meant using one two meter section of coaxial instead of doing all the testing with it. This was a more affordable way and gave great results. The final SCuNi in the Go-NoGo gauge can be seen in figure 50, it shows no red which validates the prototype and the quality of the manufactured product.

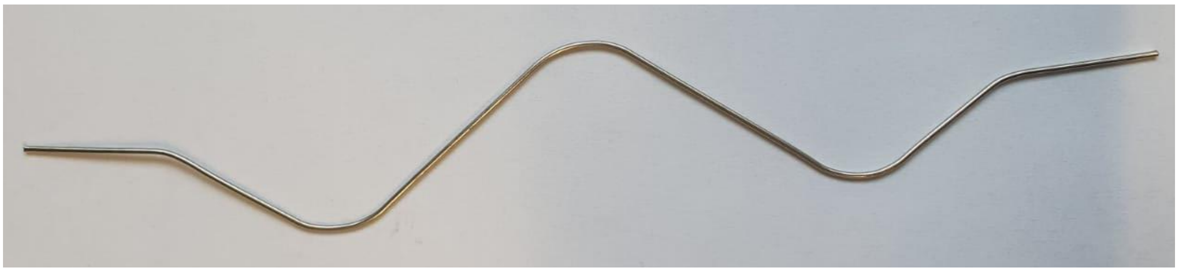


Figure 48. First coaxial to go through the machine

Figure 49. SCuNi iterations

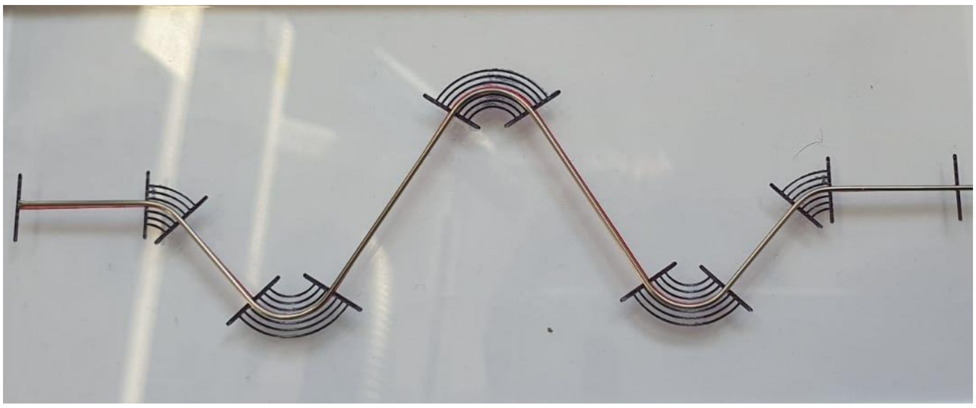


Figure 50. Final result in gauge

4.3 Results from PFMEA

1. The feeding wheels are press fitted into the motor shaft which seems to work great for a while but tends to loosen as time goes by, wheels were redesigned to accommodate a set screw which locks them properly in place.

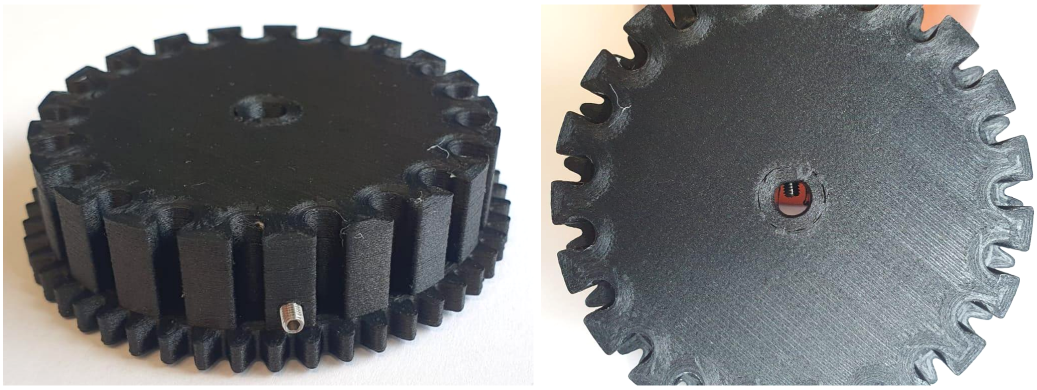


Figure 51. Set screw in feeding wheels.

2. 3D printers have a difficult time printing round objects, the result is usually an oval. This can be fixed by calibrating the printer and compensating as required. A special profile was created which calibrates the steps of X and Y axes to approach circles as much a posible. After several iterations the long and short sides are 0.15 millimeter in difference which is precise enough for the application.

3. The feeding tires are 3D printed in TPU which allows large variability in the density of the wall since they were not printed using 100% infill. Figure 52 shows the difference in fill between the wall and the knobs used to attach the tire to the wheel. This inconsistency allowed slippage and ruined the precision of the feeding part of the prototype, this is easily fixed by reprinting the tires to 100% infill.

Figure 52. Improper infill (left). 100% infill (right)

4. The tires were printed using the same calibration that compensates for roundness as the tires, this is not as critical as the wheels but the thickness of the TPU still changes and approaches more the ideal size after the calibration.

5. The front sensor has a tendency to not sense the cable when it arrives to it if the tip of the cable is pointing down or the improper tool has been used to cut it, leaving the tip crushed. Figure 53 (left) shows 10 cables passed through the prototype (no bends) with the old guide, when the length is compared there is a variance of 0.2 to 2 mm. To solve this the sensor has been lowered and a better guide tunnel printed into the guide, figure 54. The 10 cable test was repeated and the difference can be seen in figure 53 (right), where the variance is less than 0.1 mm.

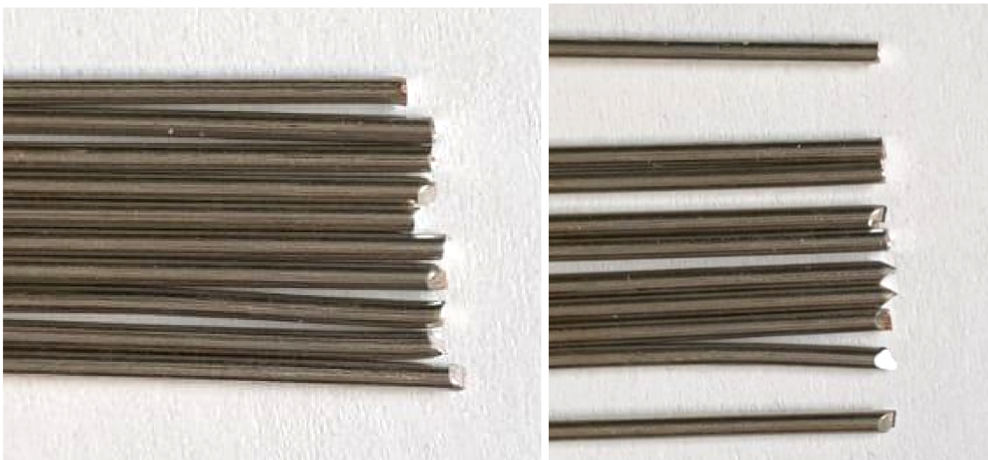


Figure 53. Variance before a new guide (left). Variance after a new guide (right).

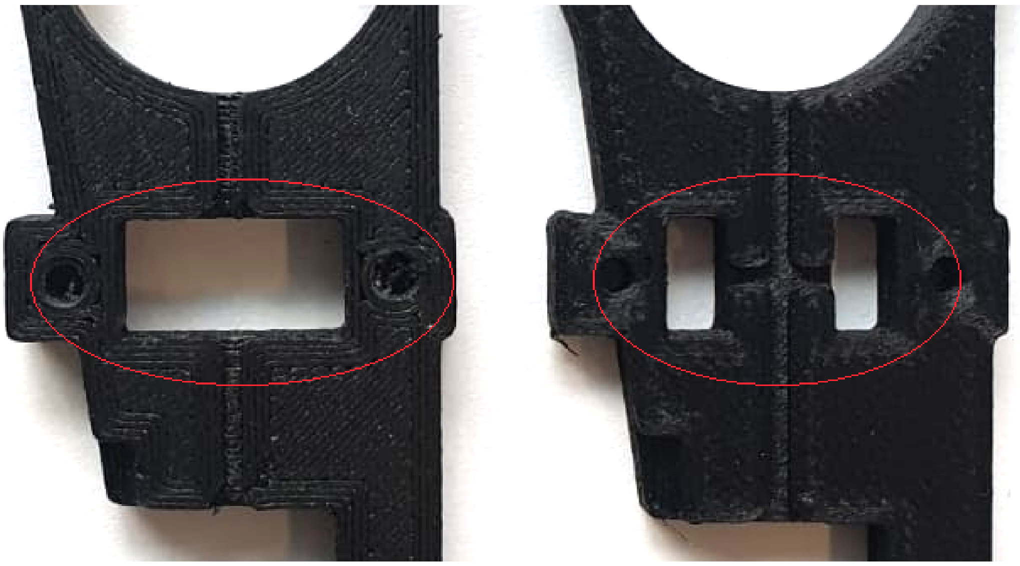


Figure 54. Difference in guide tunnels

6. The carbon fiber nylon composite material has great toughness but the infill and wall count, influence the deformation it can withstand. Parts were printed first with very low infil (10%) and a maximum of two walls, this resulted in fast print times but weak parts. Parts were reprinted with six walls and higher infill (35%). This resulted in stronger parts that can withstand the wear and tear.

7. An inductor sensor was placed in the lowest part of the bending pin solenoid to assure the program knows its position. This increases the reliability of the whole system, figure 55.

Figure 55. Induction sensor in bending pin

8. The bending pin belt was designed without a tensioner system in mind since it was expected to not change its length much considering the small forces. After some testing the belt loosen quite drastically. This caused large inconsistencies in the angle of the bends since the slack in the belt reduces the accuracy of the system. Connecting this problem with the slack in the belt could have been hard without the PFMEA since the different radiuses could have been attributed to several other problems. To solve this problem, a tensioner was designed, manufactured and installed and the quality increased drastically, figure 56.

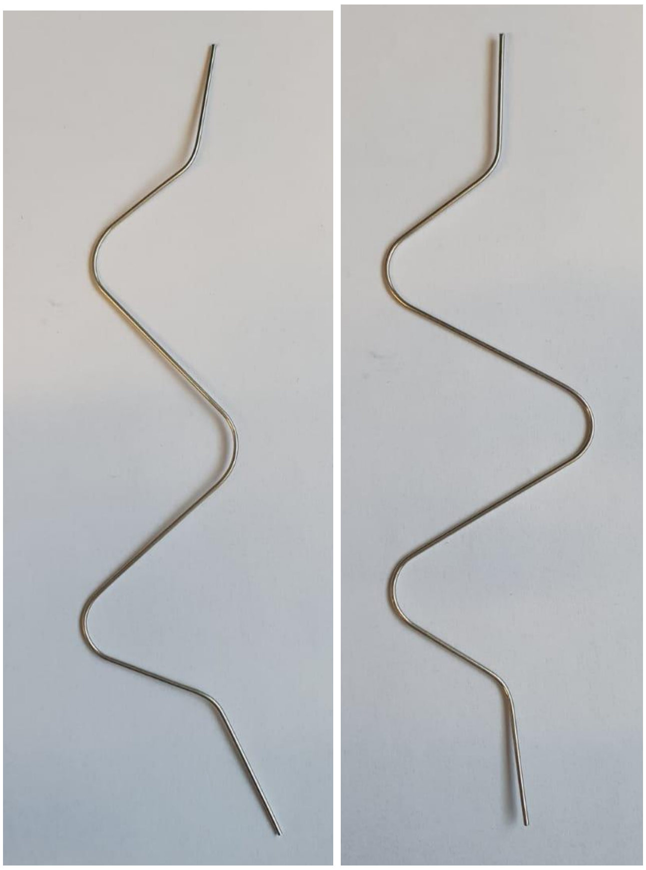


Figure 56. Variance before tensioner (left). Variance after tensioner (right).

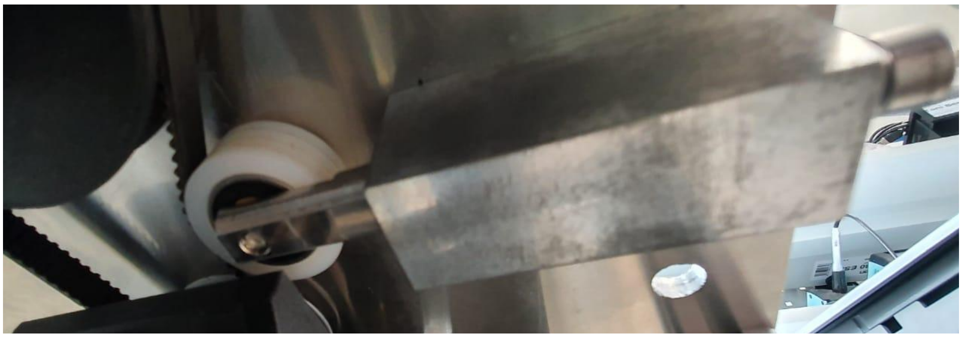


Figure 57. Manual tensioner installed.

9. The cable guides need to be parallel to the axis in which the cable moves or they will create problems like coiling when the cable is pushed against them. When the cable is fed backwards a very pronounced coil is created in the cable. This was also happening when the cable was fed to the front which would cause the bent cable to point upwards. This was solved by filleting the tunnel in the guides front and back and by tightening the tolerances to make them parallel.

Figure 58. Fillet in guide.

The rest of the problems, even though not that significant, were dealt with as follows:

- Rear sensor not sensing the cable means the machine stays off and nothing is done for this.
- Rear sensor random sensing is assumed to be too improbable for anything to be done. On top of it, if the machine starts by itself with no cable inside it would just go through its cycle without affecting anything.
- Feeding wheels being not concentric with the shaft is too improbable since the wheels are quality tested after printing is done and concentricity is checked.
- Feeding wheels not perpendicular to the shaft is improbable also, on top of this, quality control would avoid a not perpendicular wheel from being installed in the machine.
- Feeding tires with bumps would not be a problem since the tires are sanded smooth after the printing is finished.
- Front sensor randomly sensing has been hard coded to stop the machine and turn the motors off.
- Bending pin getting stuck down is also solved by the inductive sensor installed to the pin solenoid. Also, with the pin down the machine would just feed and not bend which would result in a straight wire and no damage to anything.
- If the bending belt breaks it would just stop the bending from happening and the cable would just come out straight.
- To avoid any problems with loose blades, a threadlocker was applied to the screw holding the blades.
- Blades should regularly be checked to define the maintenance time. The blades are made from hardened tool steel and the cable is soft copper which results in good performance blades.

- Cable anti coil plate distance was calibrated with precisely machined shims.
- Cable guides should be checked regularly even if their life expectancy is long, this removes the problems related to wear, also, they are fast and cheap to print.

This PFMEA results in a machine with predictable maintenance requirements and no failures on sight, which allows the research to continue towards the quality of the bent cables. This continues with the validation of the whole system while focusing on the cables.

4.4 Production capacity, quality, accuracy and repeatability

To give an answer to the research question it is essential to divide it into the basic parts that comprise it. As mentioned in the introduction the research question was established as: What is the production capacity, quality, accuracy and repeatability of the bending prototype?

The answer is as follows:

-The prototype production capabilities were measured when the prototype was capable of receiving a two meter section of cable and fully processing it with the aid of a technician. The required daily cables are established as 150-250, which is the target the production speed tried to achieve.The results are explained in the following table.

Table 7. Production capacity

Process	Required time
Prepare the prototype at the beginning of the shift	600 seconds
Feeding the cable to the prototype	15 seconds
Prototype goes through whole two meter section producing eight cables	720 seconds
Sort cables	60 seconds
Feed next cable	15 seconds
Turn off machine and clean	600 seconds
Total time	2010 seconds

In an eight hour shift the amount of cables produced is 260. This is converted to the average time to produce one cable of 110 seconds. While this is not exceptional speed it is enough speed to match the current demand and to not over produce cables since the rest of the process is still done by the technicians (stripping the tips and soldering the connectors). It is important to mention that the program is being executed at 30% speed and the motors are at 25% speed and 30% torque.

-The quality of the final cables was determined by the use of the gauges and the following requirements. Tolerances are not tight enough to define them, visual inspection with the gauge is defined as enough.

> -The bends should start and end in the spot marked by the gauge, the most important part is that the straights after and before the bend line up with the gauge line.
>
> -The bends should cover the red line properly which is precisely the thickness of the cable.
>
> -The beginning and end straight feeds should be parallel, this is checked with gauge one.

As previously showed the quality achieved by the bending prototype fulfills all of these requirements.

The quality also includes the cut cross sectional geometry comparing the old method which was hand clipped to the new blade geometry. Figure 59 shows the difference in quality, while hand clipping ovaled the tip, the new blades leave the ends more round, which is important for the current stripping machine. This is a very positive result and a large improvement in the cable quality.

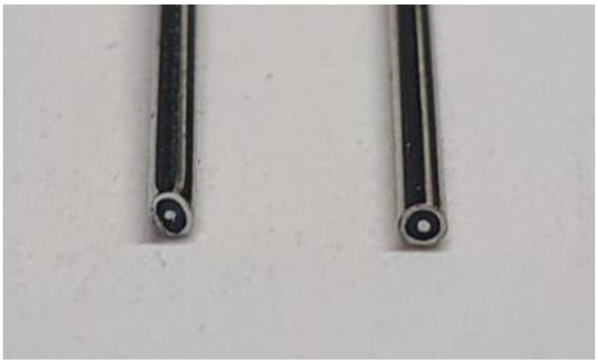


Figure 59. Cutting quality

-The accuracy of the cables is a very important metric which actually changes the signal in the cables, this is where the tighter tolerances were expected and the prototype surpassed the expectations lowering the tolerances from +/- .5 mm to +/- .2 mm making the calibration of the final cables easier and more predictable. This is the most important result that the prototype gave.

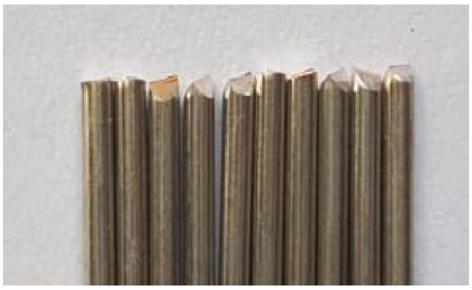


Figure 60. Accuracy results

-The prototype is also expected to produce the same geometry if it makes one cable or a hundred. This was tested by validating the geometry of one cable every twenty manufactured until a hundred. Figure 61 shows the results which validate the repeatability of the prototype.

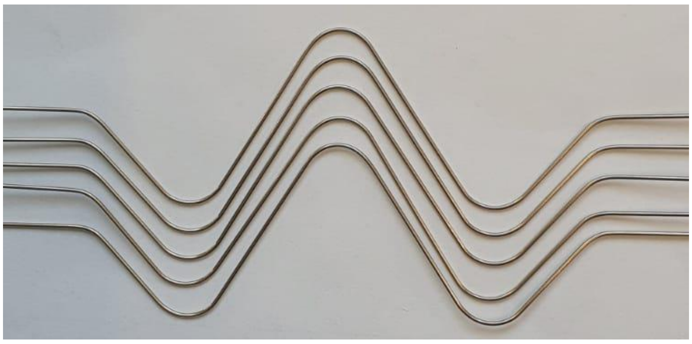


Figure 61. Repeatability results (top to bottom 1, 20, 40, 60, 80, 100)

5 Discussion

The literature says that the quantum computer capabilities are expected to grow exponentially the same way microprocessors grew in classical computers (Krinner, 2019). This begs for a lot of further research into the automation of the manufacturing of the parts that make a quantum computer, the cryostat alone has hundreds of parts and processes that will require automation. While for now, mechanical engineering, mechatronics and automation are required, soon the focus will shift to MEMS engineering since the shrinking of parts will always follow the increase of requirements. It is important that the research done by physicists and scientists have a good backing from engineering innovation so the progression never gets halted.

5.1 About results and the PFMEA

The values in the PFMEA worksheet have been assumed with a good knowledge of the functionality of the machine and the importance of its parts to the final product. The worksheet can always be tweaked after the PFMEA and validation are completed, this allows more precise values to be added. This was outside the scope of this research and it was assumed that the values selected were appropriate to validate the prototype.

The results obtained by the PFMEA used for this prototype helped increase the lifetime of the prototype, its manufacturing quality and its reliability. The problems with roundness in the 3D printed parts have been noted and a whole process to tune the 3D printers has been developed. This helps accelerate the manufacturing of replacement parts required as the prototype continues its development. The possible issues that the prototype could encounter by jamming and damaging itself have been addressed by placing a safety net of sensors all around the prototype, this would have been a difficult task to do by guessing what was required but was instead a straightforward process thanks to the PFMEA. This safety net around the prototype is the most important improvement achieved by the PFMEA since without it the quality of the manufactured cable and the safety of the machine were on the line.

The PFMEA approach for this prototype seems to be an easy way to move forward and it is a really powerful tool in the validation of any process which includes machines or assembly lines. It can be used for small processes or fully blown out manufacturing plants. The focus in splitting things into the building blocks of the process allows any size of process to be managed and checked thoroughly.

The cable force and springback apparatus was an invaluable tool for understanding how the mock cable behaved and which different options were available. It also allowed the springback variable to be calculated accurately which allowed a simple and fast change from SnCu to SCuNi. This time saving was important in allowing the research to focus more on the prototype validation and quality without having to play around with values but instead have an understanding of what was required.

The production capacity was decided to be enough for the current cable demand, and the limitation posed by manually post processing them. The speed of the prototype was selected to approach as much as possible the expected quality; surely the speed can be increased with little to no effect in the quality of the final cable but since it was not required it was not included in the scope of this research.

Regarding the bend quality, it needs to be such that in the tight packing of the cables there is no contact between cables since this would introduce heat to the system and reduce its efficiency drastically, on top of this good bend quality provides a visually pleasing assembly which is an expected plus in the manufacturing of these bleeding edge technologies. Thanks to the prototype and the precision of the bends, tighter packing than previously thought was achieved, increasing the capabilities of the cryostat.

The repeatability of the prototype is essential since there would be no point in having precise cables only for a certain amount of time and then creating waste until the error is noticed. Since the packing is so tight, defective cables cannot be utilized which could quickly become a very expensive error. This also includes the precision in length of the final cable, since shorter cables or out of spec ones cannot be used.

With all this considered it was decided that these results allow the prototype to go into production and relieve some workload from the already overwhelmed technicians while further development continues.

5.2 Limitations

The PFMEA worksheet could be benefited from having a diverse team filling it, this allows different points of view to be introduced into fixing and preventing problems in the final process. It will always be better to have a multidisciplinary team than a single person checking it through. It is important to mention that the process flow diagram should be evaluated several times in a row for it to be truly effective.

It is also important to mention the limitations of the gauges, they will be relying on the user for their proper functioning since the user will decide if the red lines are visible or not, which in reality introduces human error into the process but is overlooked by the scope of this research. This can be changed by creating a jig that holds a camera directly on top and has a screen to show the results to the user. It would also require a jig where the user could only place the cable in a specific place. This could be implemented in further research but it was decided that the compromises are acceptable for this research.

5.3 Suggestions for further research

It is important to mention that the automation of the manufacturing of these cables is far from over since they still need to be stripped from the ends and a connector needs to be installed at each end. This is a great opportunity for further research which could include the design of the next machines and their validation. The final step would be the integration of the several machines to have a fully developed production line manufacturing finished coaxial cables, and the validation for this whole system.

Some further developments which were not included in this research since they were out of the scope are the KPIs. The KPIs are really important to keep in mind when the machine starts full production and it is relied upon by the manufacturing line. It is important to observe the different factors affecting the machine and being affected by it. There needs to be a constant quality control check and tune to reach the expected KPIs. This will give information on which parts are unreliable or if there needs to be any redesign based on wear or tear when thousands of cables are produced.

Computer vision would be an invaluable addition to a machine like this, and deserves its own specific research. It can focus on the quality of the cables but also in training the AI to compensate for the differences that the residual forces inside the coaxial cables, left by the drafting process during the manufacturing, induce into the final bent cable.

6 Conclusions

This research's main focus is to help advance the manufacturing of quantum computers as a benefit to humanity. The road is long and complex but small steps taken throughout different people, universities and research centers is what this technology needs to achieve its full potential.

Quantum computing is on the way to becoming one of the most influential technologies in human history. The ability to be able to simulate complex quantum systems will permit the acceleration in development of highly needed technologies in a wide variety of areas. Medicine, genetics, climate sciences, engineering, material sciences, etc. will see a great boost in discoveries and technological advances. For all of this to happen, research into the problems or limitations blocking further development needs to be funded and pushed forward. Technical limitations will jump science fields fairly quickly and constantly. As of now the main areas required for this development can be roughly divided in computer science, material sciences, manufacturing and R&D. This specific research focused on the manufacturing part, specifically in the superconductive cables used to communicate with the quantum chip. The automation of the manufacturing of these cables has been lagging behind since the required amounts have not yet been enough to justify the development of a machine to do it, until now.

This research was done to validate and calibrate a prototype to measure, bend and cut the coaxial cables with high accuracy and repeatability. A process specific failure mode and effects analysis (PFMEA) was followed to identify the main failure areas which were tackled one by one. The quality of the prototype and the final cable speak on behalf of the power of using the correct validation tools like the correct type of FMEA. It is important to mention that results will always be obtained regardless of the method used, but the results from a correctly executed experiment with the correct method will always be superior. The prototype was validated and the quality of the manufactured cables exceeded the requirements.

The validated prototype was used in pair with Go-NoGo gauges to validate the quality of the manufactured cable. Improved Go-NoGo gauges could be used to eliminate the human error in the quality control, this could allow the quality to improve further, more precise jigs with computer vision integration could be implemented. The gauges could also be completely eliminated and a camera with computer vision could analyze each cable the moment it comes out validating its quality. This would allow computer vision to be used all over the machine to also prevent problems, detect slippage in the bending gear or the feeding wheels, analyze the wear in the bending ring, slack in the bending pin, etc. Computer vision is an extremely powerful tool which would be greatly suited in this application but is out of the scope of this research.

Further research could focus on the optimization of speed while maintaining quality. There are many reasons for the speed selected, the main being that the production requirements are still low. As mentioned in the introduction, quantum computers are moving forward at a really fast pace and the time that a machine like this will be sufficient will not be long. In the near future the most logical solution would be to manufacture more machines to meet demand.

The research proved to be effective in achieving the goals laid out in the introduction. The prototype fulfilled the production capacity, quality, accuracy, and repeatability expressed in the research question. This prototype will be a useful tool for the manufacturing and further development of quantum computers, while this research will be a great map for the validation of prototypes or processes.

By the time this research was completed hundreds of cables have been manufactured as the result of a proper validation and calibration of the prototype, the gauges help continue the quality control and allow the technician to verify that everything is working properly.

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